

FIRST RESULTS FROM THE NOVA EXPERIMENT

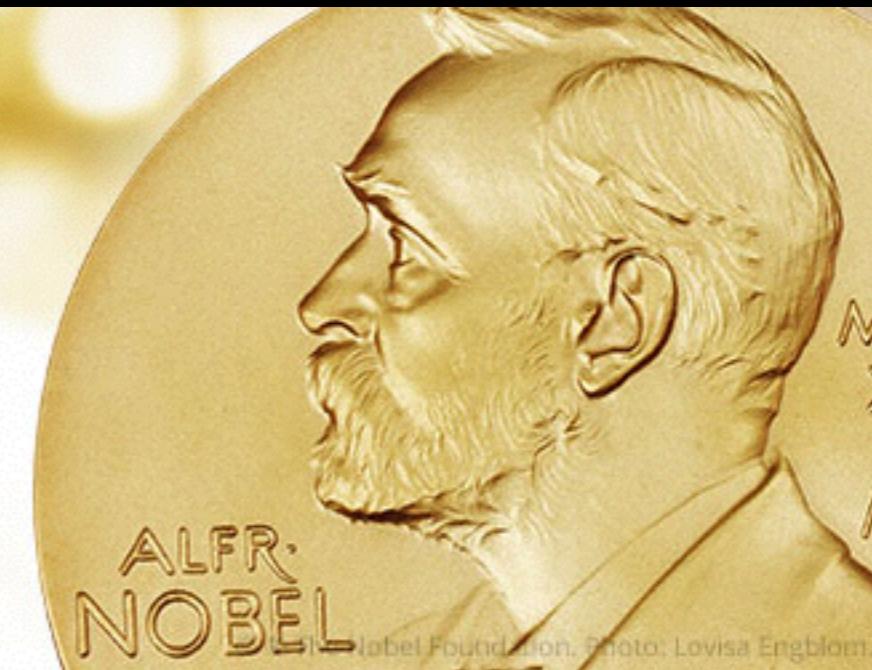
MAYLY SANCHEZ
IOWA STATE UNIVERSITY

FNAL Neutrino Seminar — December 10, 2015

"For the greatest benefit to mankind"
Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

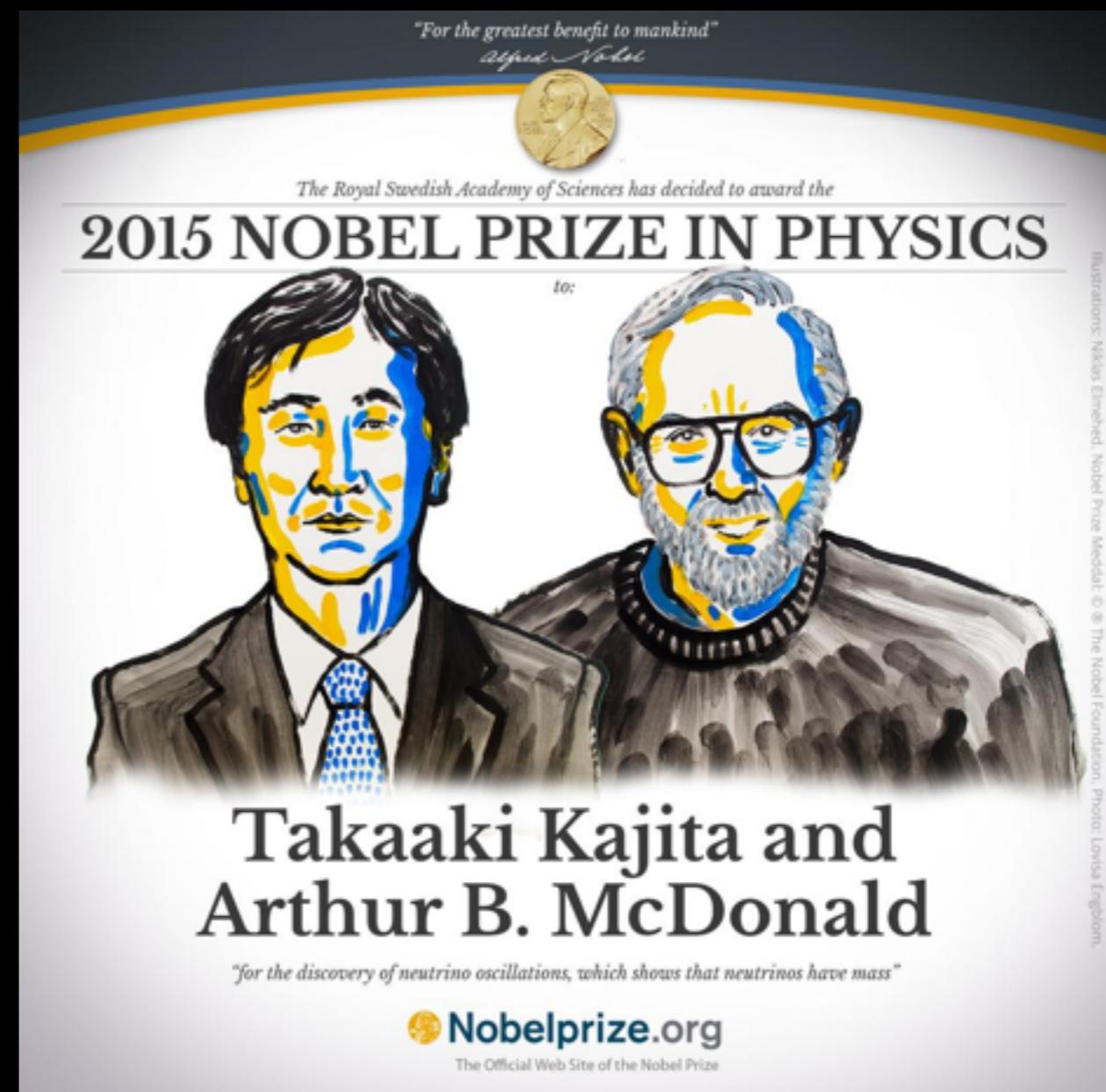
Takaaki Kajita
Arthur B. McDonald



THIS YEAR'S NOBEL PRIZE

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

SEE S. PARKE COLLOQUIUM

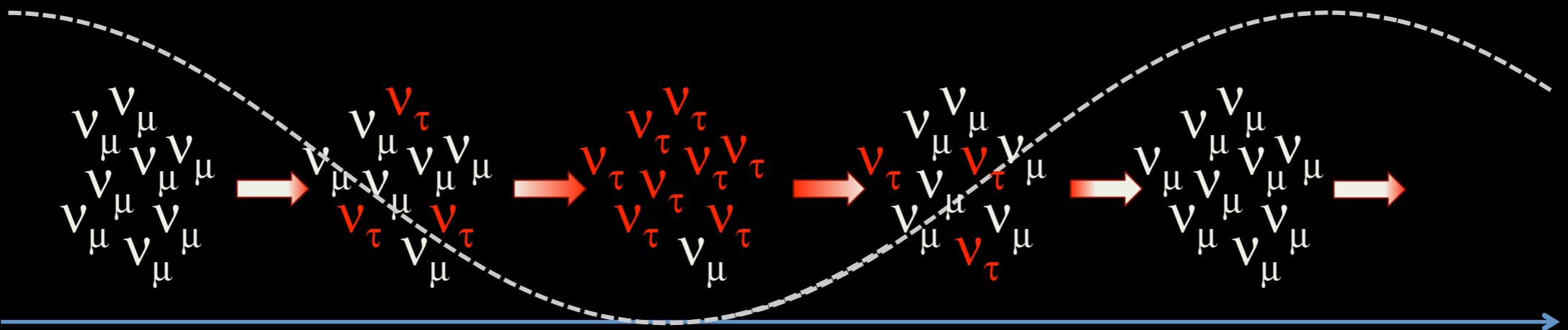


Takaaki Kajita and
Arthur B. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Nobelprize.org
The Official Web Site of the Nobel Prize

NEUTRINO OSCILLATIONS



- Three flavor eigenstates are linear combinations of the mass eigenstates:

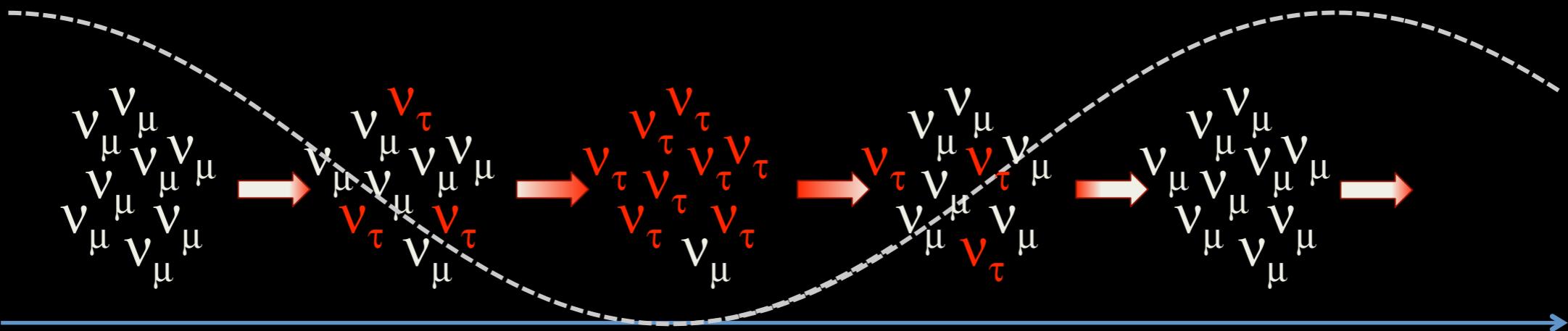
$$|\nu_\alpha\rangle = \sum_{k=1}^n U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

- There is thus a non-zero probability of detecting a different neutrino flavor than that produced at the source:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- The probability depends on the distance traveled and energy (experimental parameters) as well as the mixing amplitudes and the difference of the square of the masses (Nature's parameters).

NEUTRINO OSCILLATIONS



- Three flavor eigenstates are linear combinations of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_{k=1}^n U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

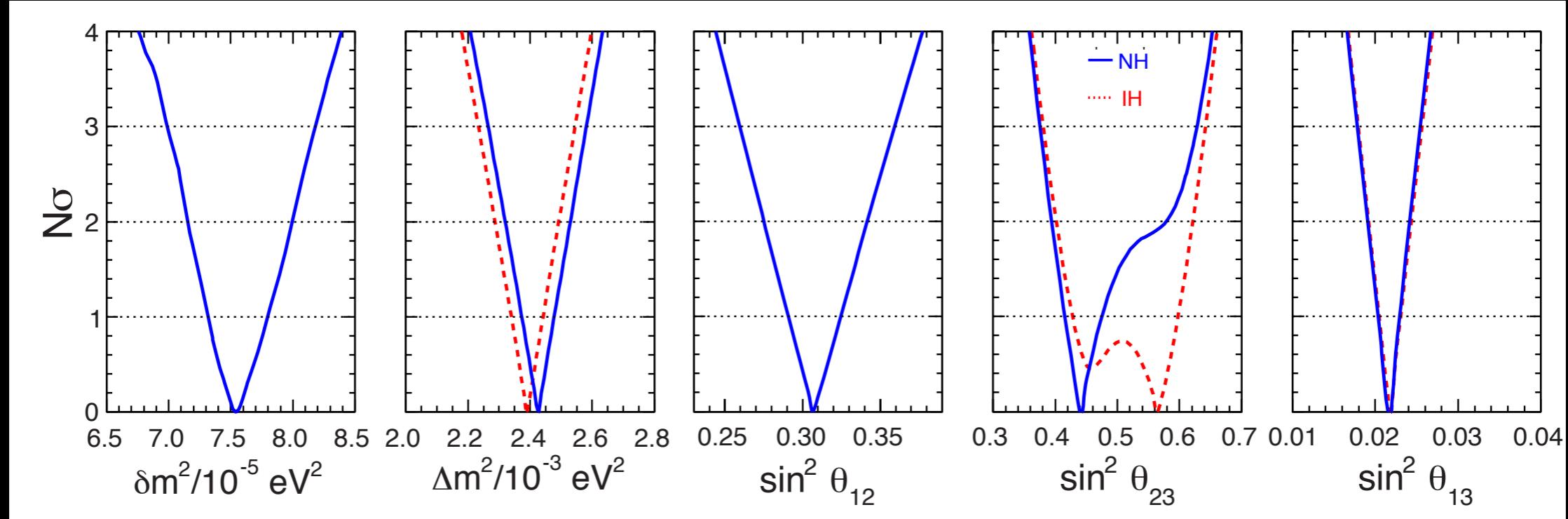
- Where the mixing matrix has 3 mixing angles and one phase (ignoring Majorana):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- The **(12)** sector: **Solar + Reactor**, L/E 15,000 km/GeV
- The **(23)** sector: **Atmospheric + Accelerator**, L/E 500 km/GeV
- The **(13)** sector: **Reactor + Accelerator**, L/E 500 km/GeV

NEUTRINOS MASSES AND MIXING

How well are these measured?



Accuracy (2014):

SOLAR	δm^2	2.6	%
ATMOSP.	Δm^2	2.6	%
SOLAR	$\sin^2 \theta_{12}$	5.4	%
REACT.	$\sin^2 \theta_{13}$	5.8	%
ATMOSP.	$\sin^2 \theta_{23}$	~10	%

- Global analysis presented by A. Marrone at TAUP 2015 (before NOvA results).
- This analysis combines the World's data from solar, reactor, atmospheric and long baseline neutrinos.

EXPERIMENTAL PICTURE EVOLVING QUICKLY!

THE NOVA EXPERIMENT



THE NOVA COLLABORATION

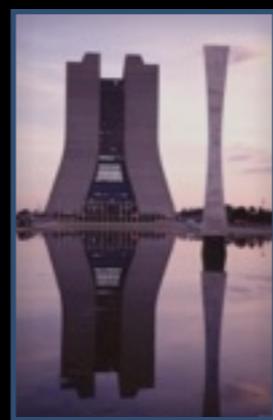
40 Institutions from 7 countries
over 200 collaborators



Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Indian Institute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · **Iowa State University** · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · College of William and Mary

THE NOVA EXPERIMENT IN A NUTSHELL

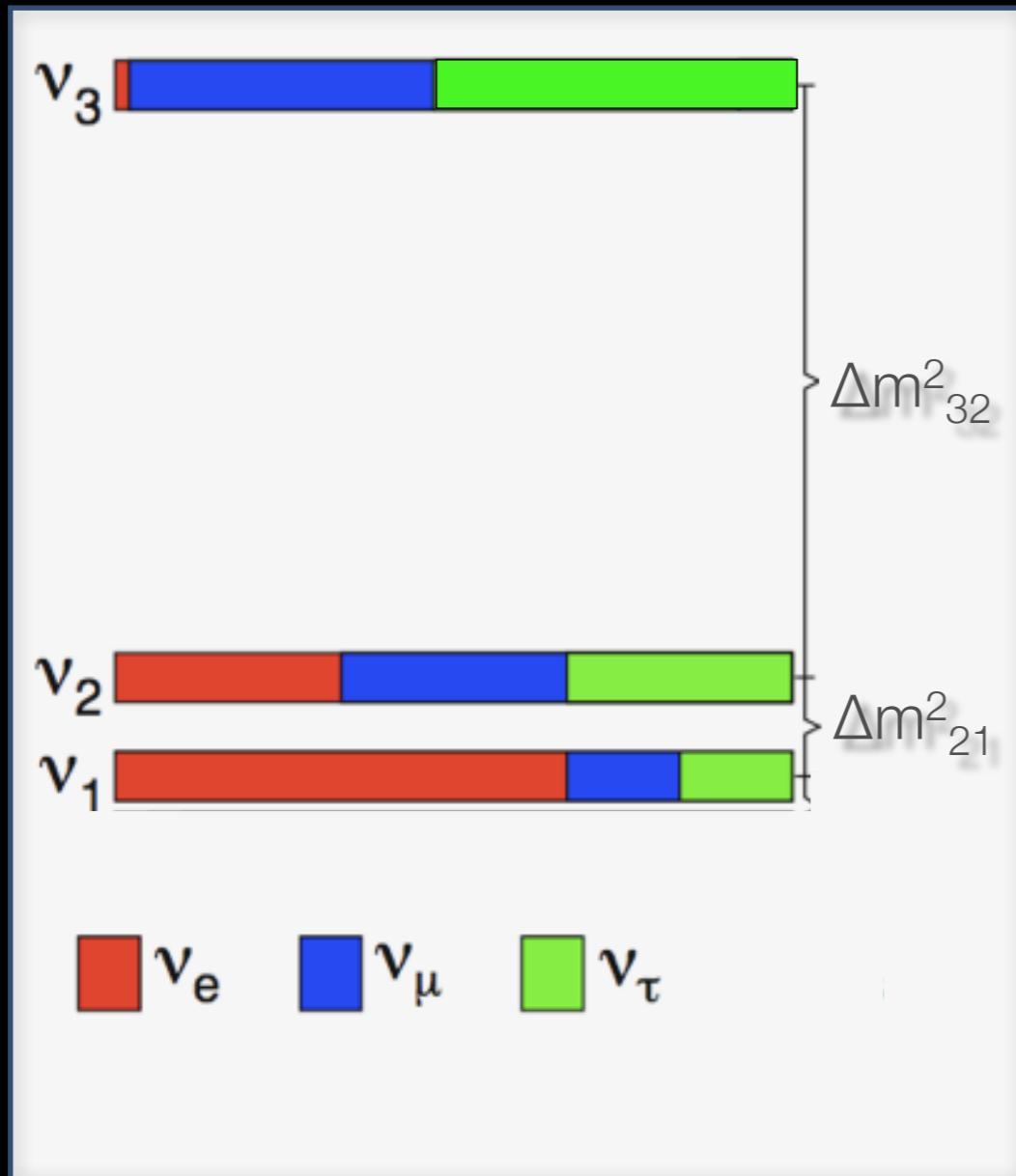
- Upgrade existing high intensity NuMI **beam of muon neutrinos** at Fermilab from 350 to 700kW.
- Construct a highly active liquid scintillator **14-kton detector** off the main axis of the beam.
- If neutrinos oscillate, **muon neutrinos disappear** as they travel and **electron neutrinos appear** at the Far Detector in Ash River, 810 km away.



2nd generation
← long baseline →
L/E ~ 500 km



THE GOALS OF THE NOVA EXPERIMENT



FIRST STEP OBSERVE
DISAPPEARANCE AND
APPEARANCE FOR
NEUTRINOS

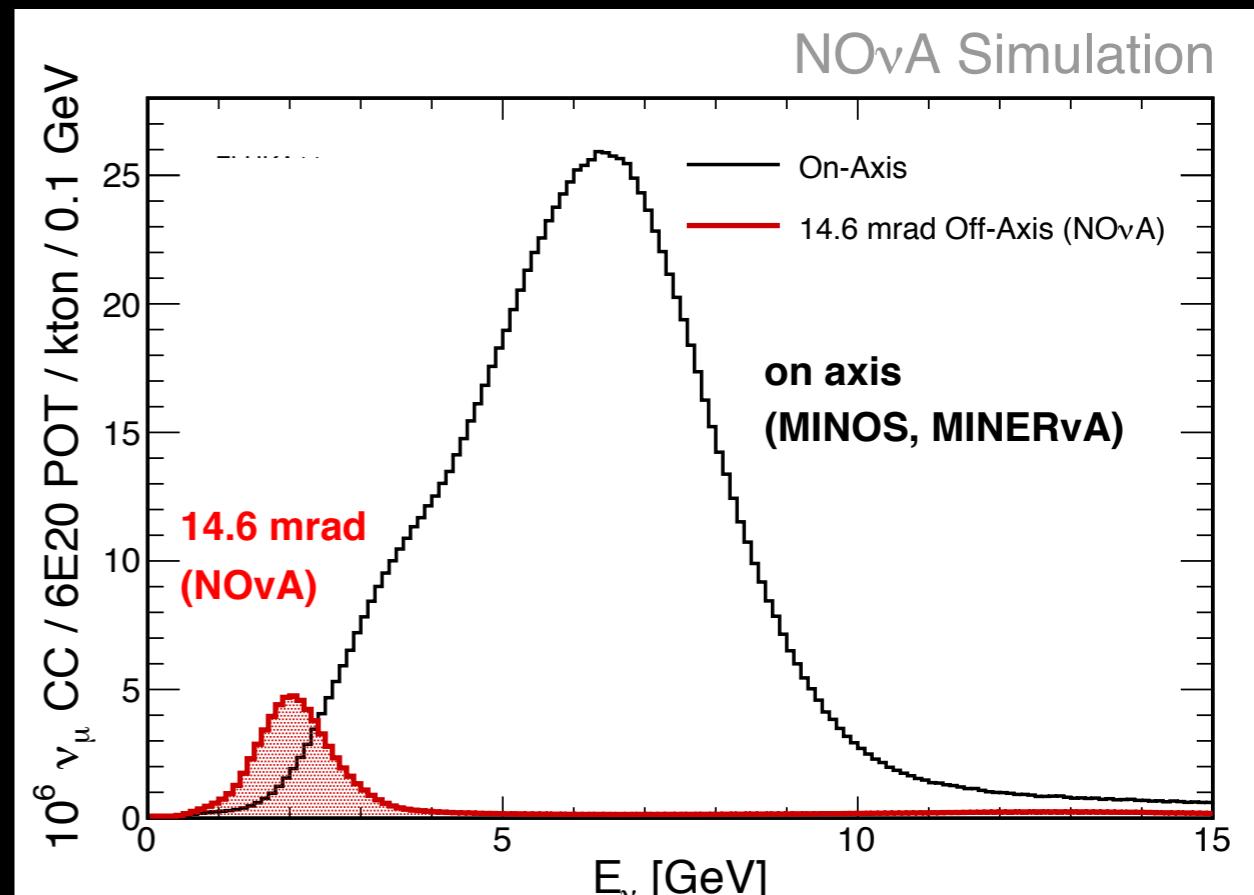
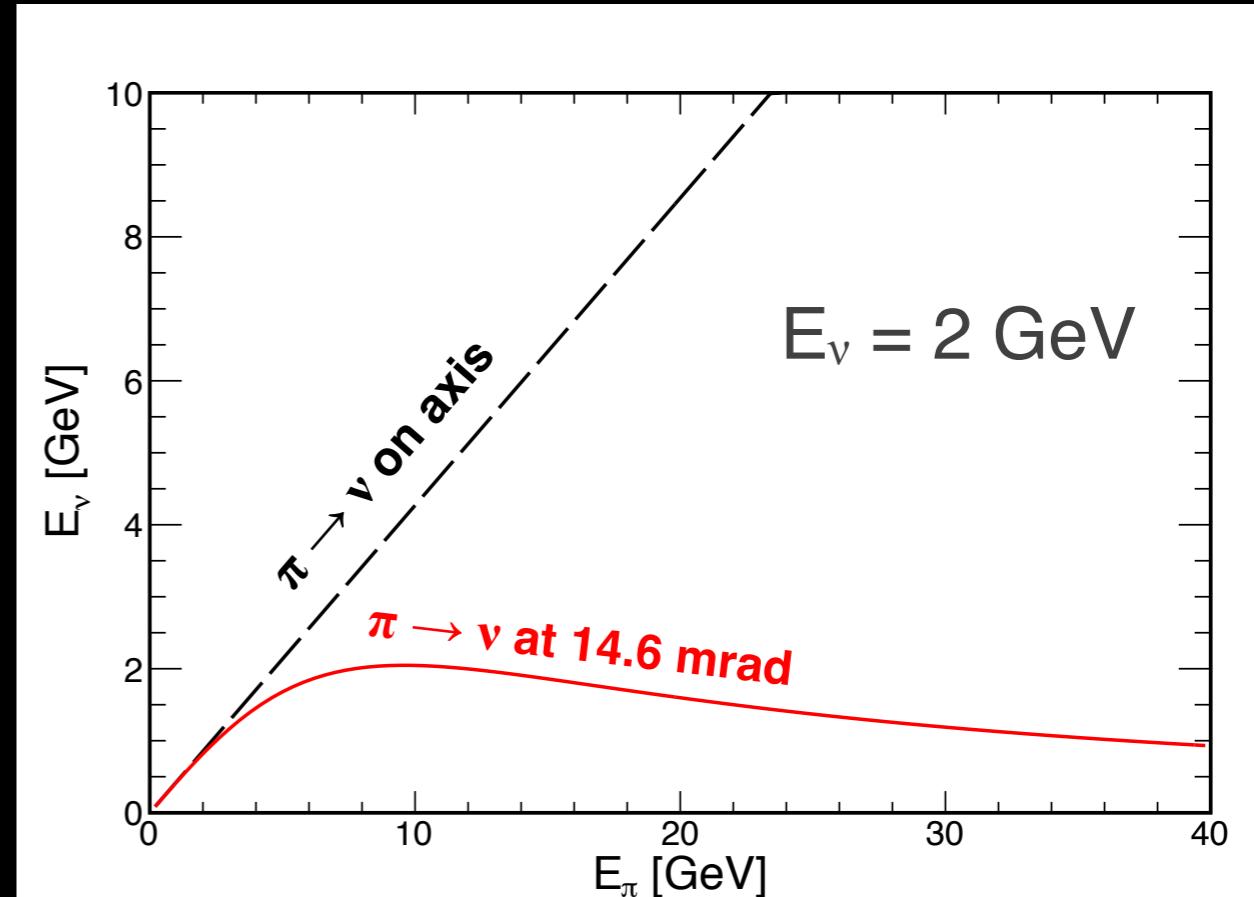
- Measure the oscillation probabilities of $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ as well as $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
- Precision measurements of Δm^2_{32} , θ_{23} .
- Determine neutrino mass hierarchy.
- Study the phase parameter for CP violation δ_{CP} .
- Resolution of the θ_{23} octant.
- As well as:
 - ν cross sections (first result presented at NuINT by X. Bu) and interaction physics.
 - Sterile neutrinos.
 - Supernovae and monopoles!

THE OFF-AXIS NUMI BEAM

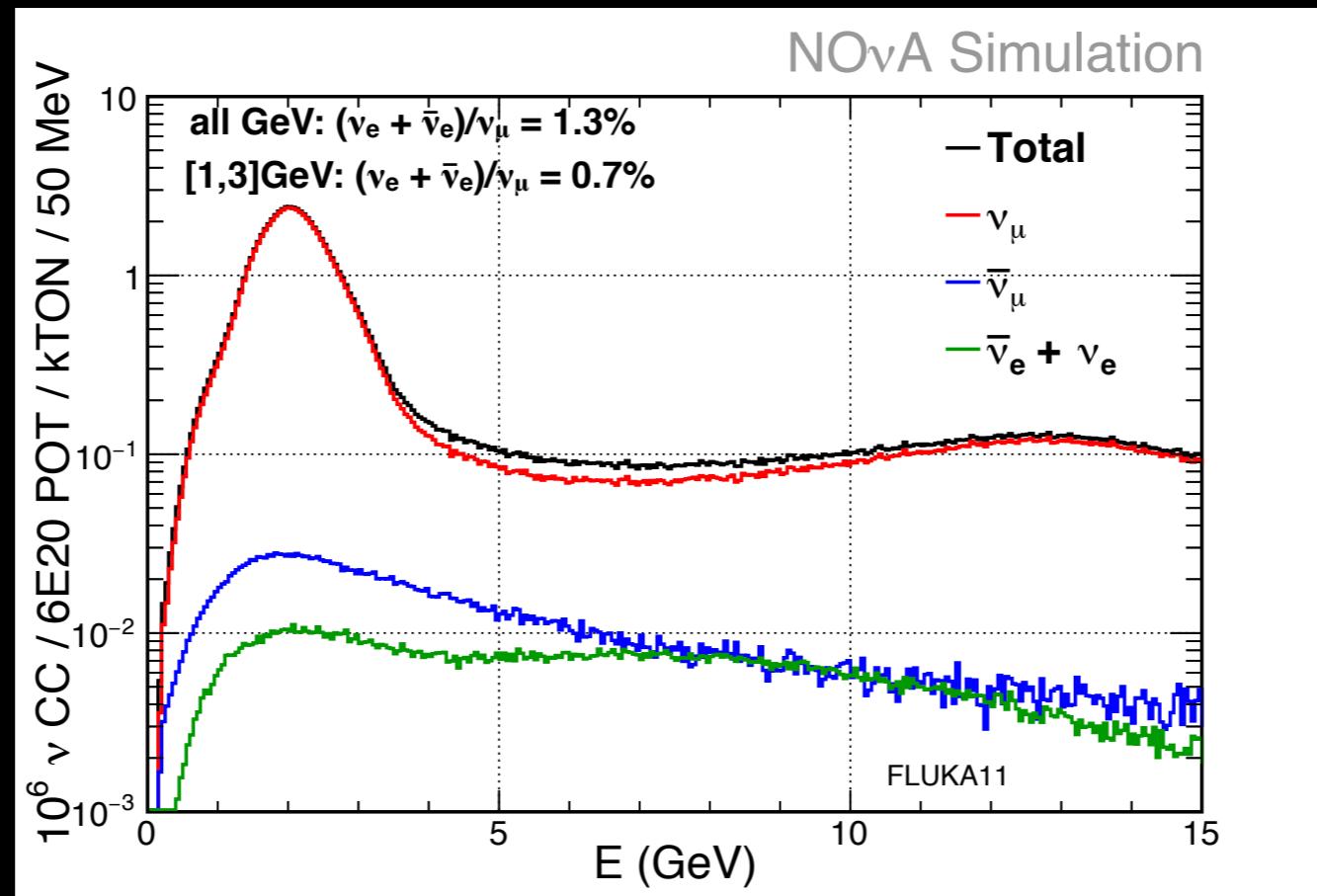
- NO ν A detectors are located **14 mrad** off the NuMI beam axis.
- With the **medium-energy NuMI** configuration, it yields a narrow 2-GeV spectrum at the NO ν A detectors due to meson decay kinematics:

$$E_\nu = \frac{1 - (m_\mu/m_\pi)^2}{1 + \gamma^2 \tan^2 \theta} E_\pi$$

- Location reduces NC and νe CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV.



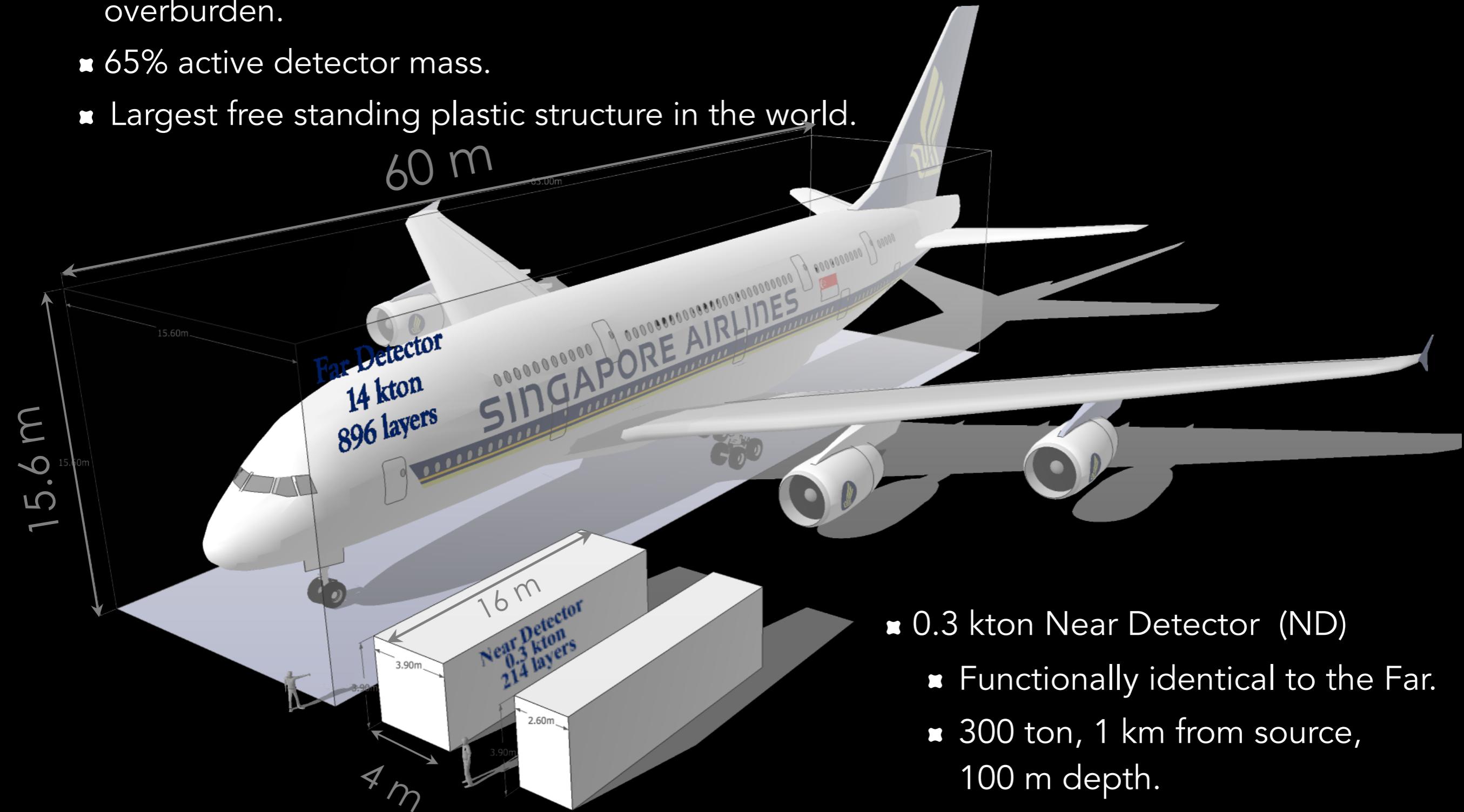
THE OFF-AXIS NUMI BEAM



- In FY15 NuMI beam routinely operated at 400 kW for NOvA.
- Overall uptime: 85%. Peak intensity of 520 kW achieved.
- A total of 3.45×10^{20} POT delivered is used for these analyses equivalent to 2.74×10^{20} POT with full 14 kton detector.
- Data taken from February 6, 2014 and May 15, 2015 with detector still under construction.

THE NOVA DETECTORS

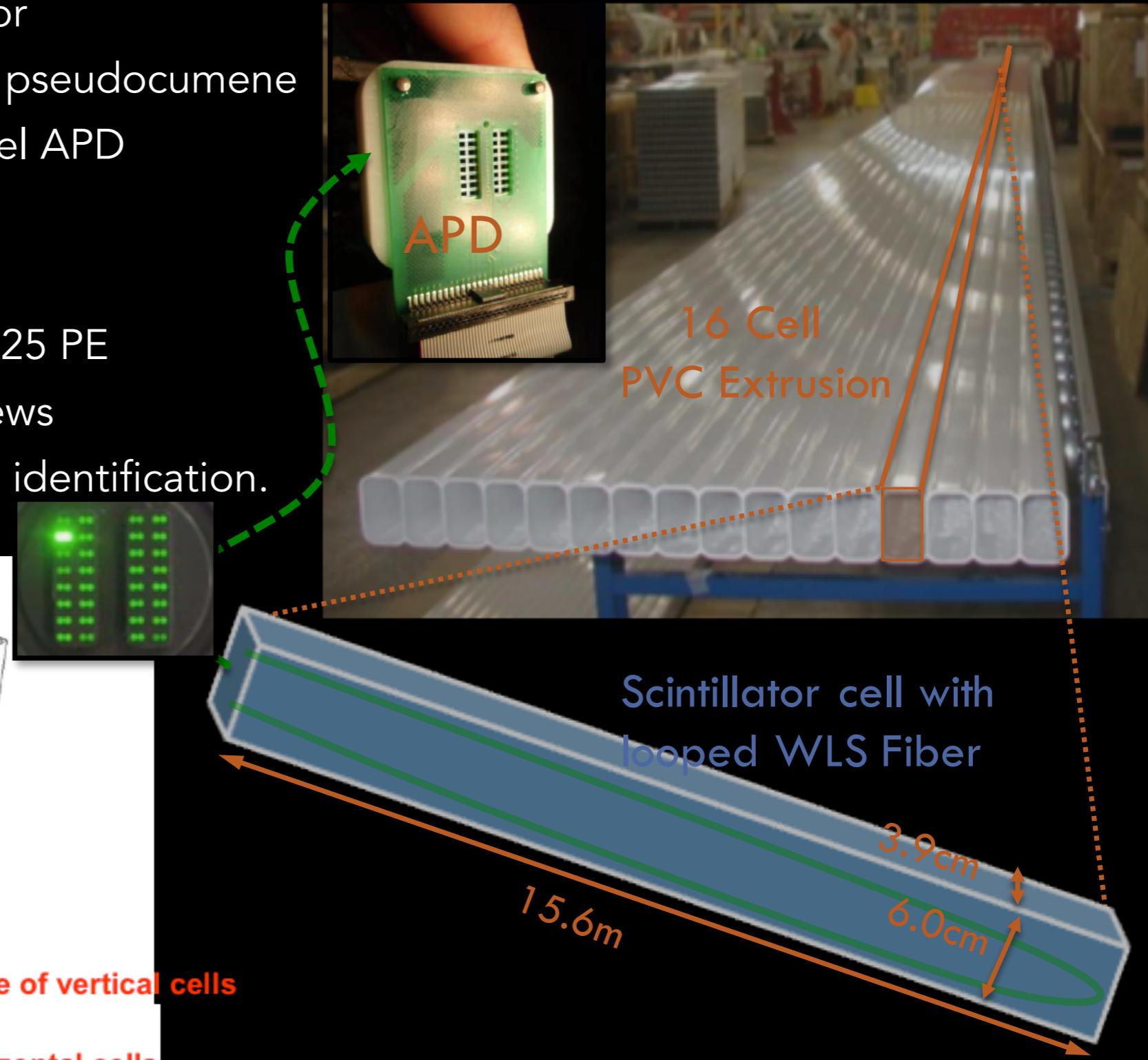
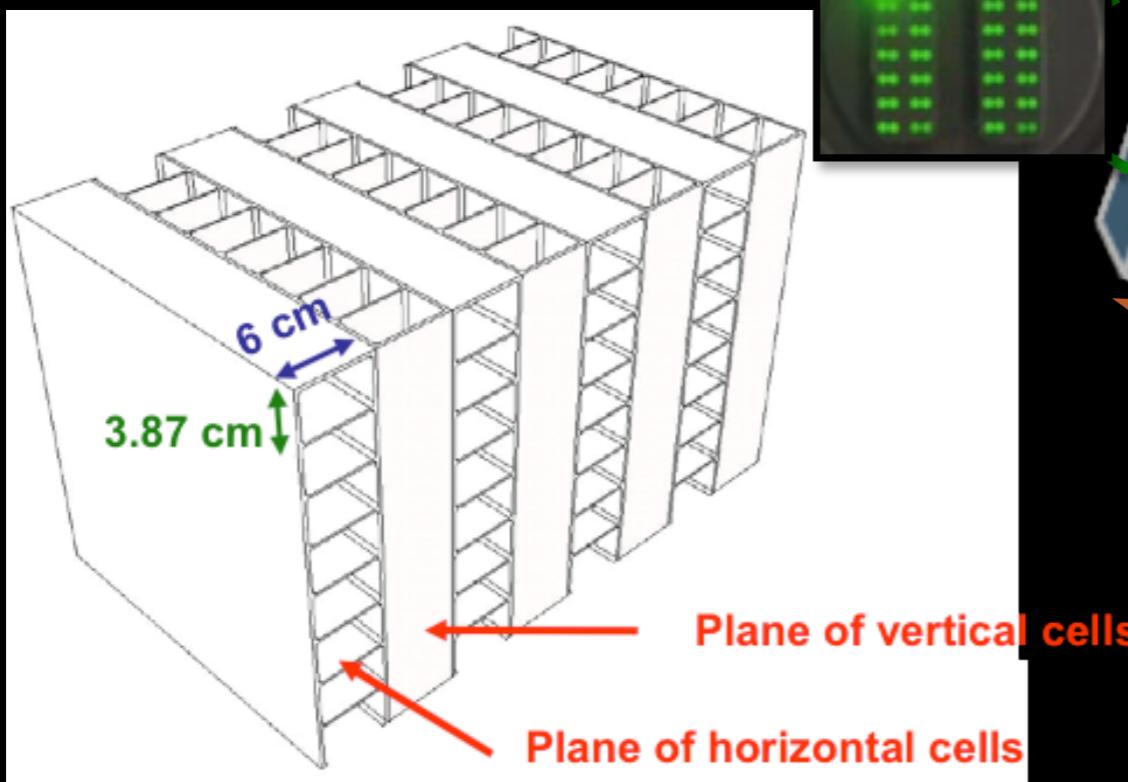
- 14 kton Far Detector (FD), low-Z, tracking calorimeter.
- 810 km from source, on the surface, 3 m.w.e. overburden.
- 65% active detector mass.
- Largest free standing plastic structure in the world.



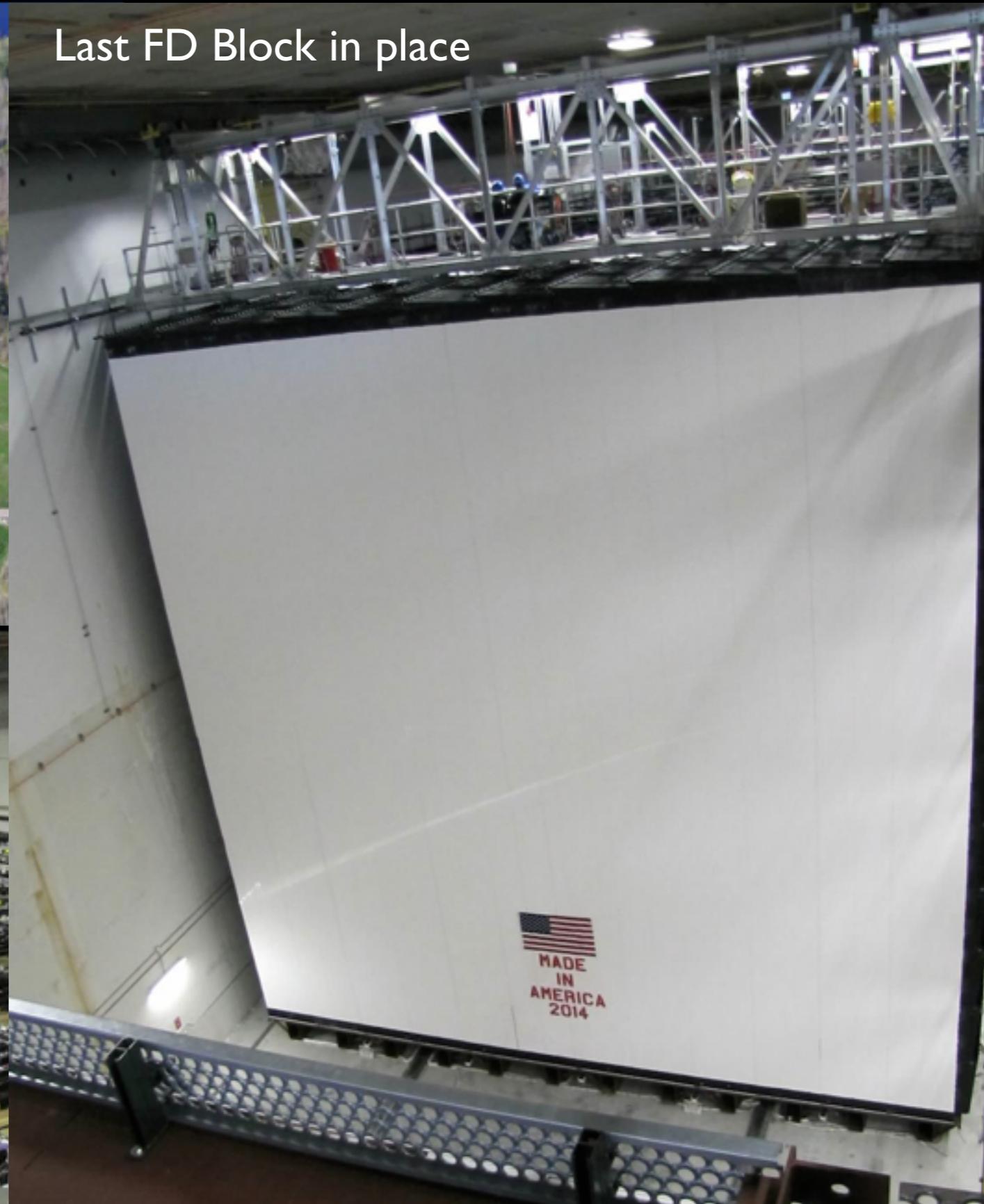
- 0.3 kton Near Detector (ND)
- Functionally identical to the Far.
- 300 ton, 1 km from source, 100 m depth.

THE NOVA DETECTORS

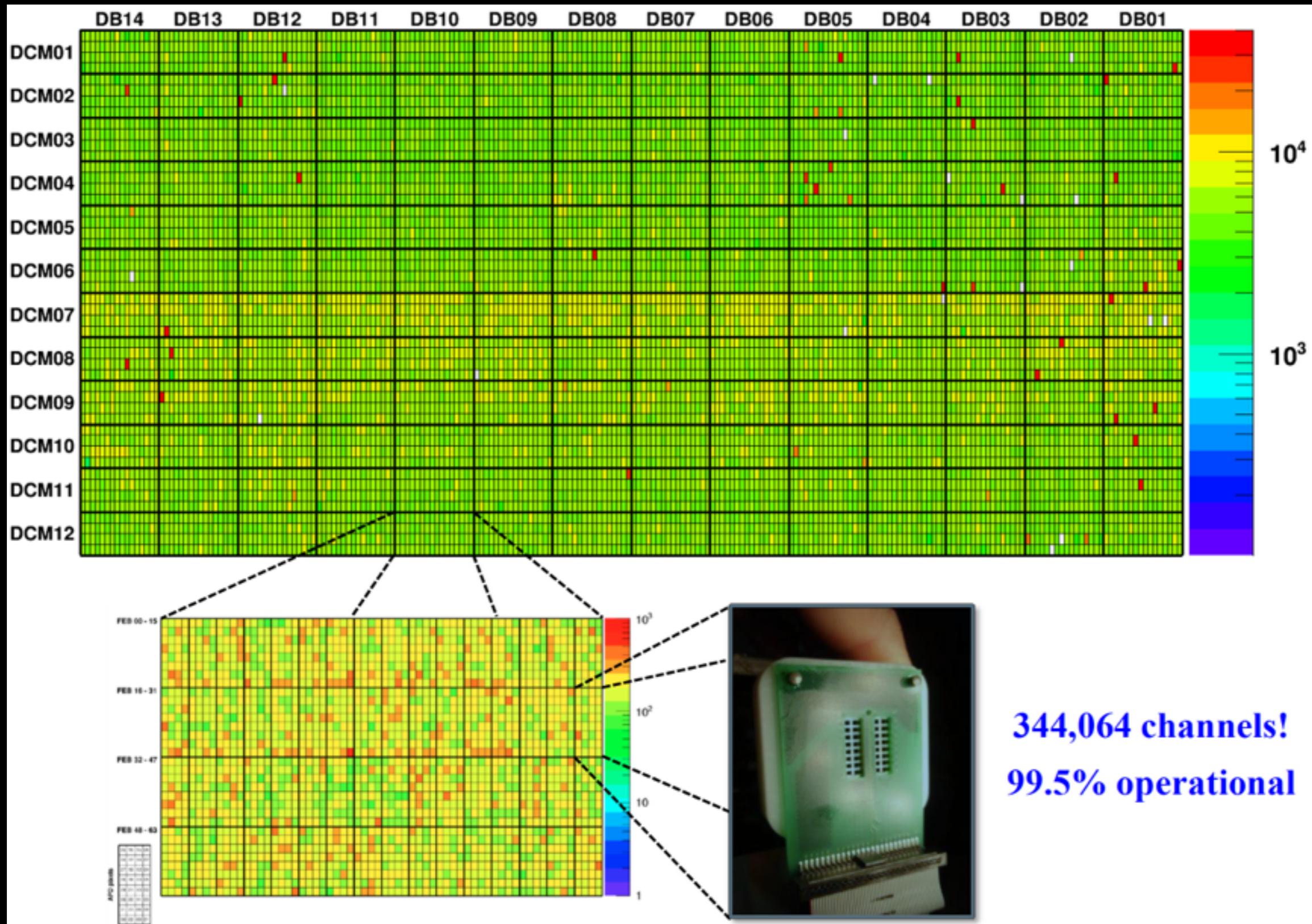
- PVC extrusion + Liquid Scintillator
 - 11M liters of mineral oil + 5% pseudocumene
- Read out via WLS fiber to 32-pixel APD
 - FD has 344,064 channels
 - ND has 18,000 channels
 - muon crossing far end at FD~25 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer, excellent for e- identification.



THE NOVA FAR DETECTOR



THE NOVA FAR DETECTOR

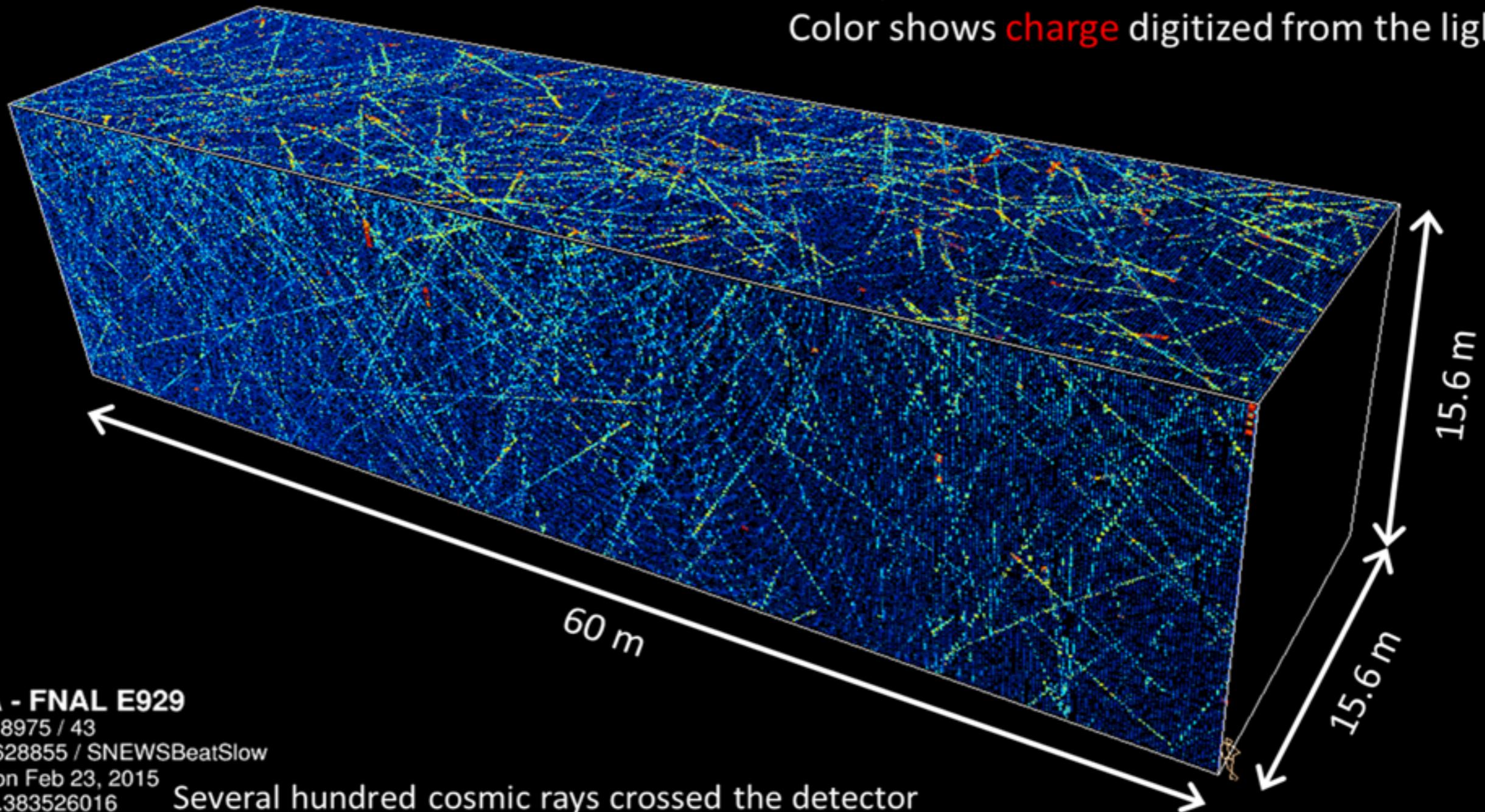


BUT WHERE ARE THE NEUTRINOS?

5ms of data at the NOvA Far Detector

Each pixel is one hit cell

Color shows **charge** digitized from the light



NOvA - FNAL E929

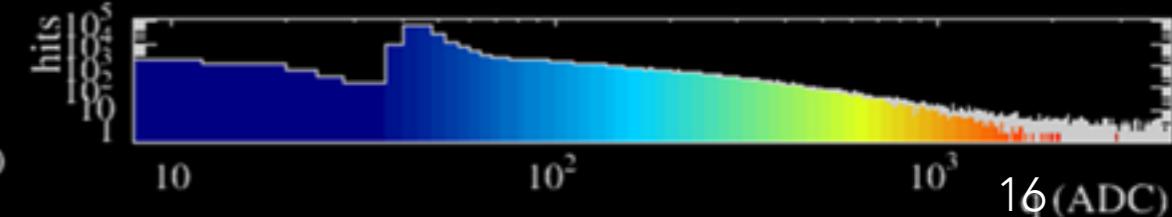
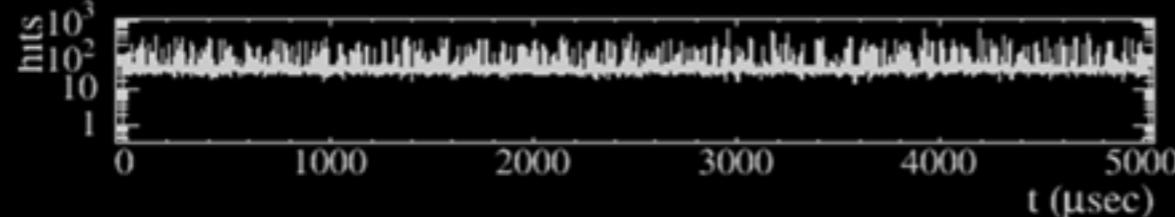
Run: 18975 / 43

Event: 628855 / SNEWSBeatSlow

UTC Mon Feb 23, 2015

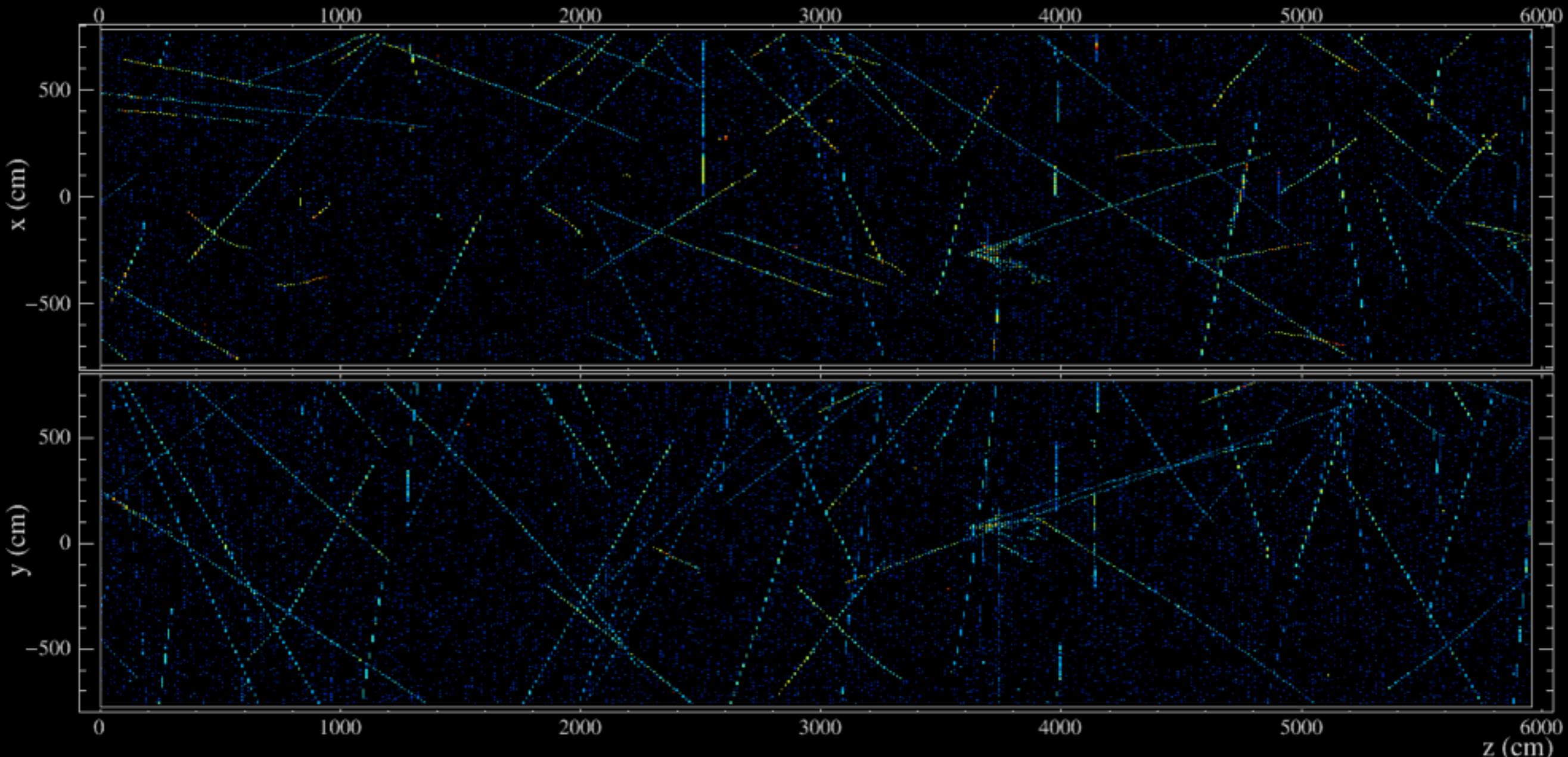
14:30:1.383526016

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)



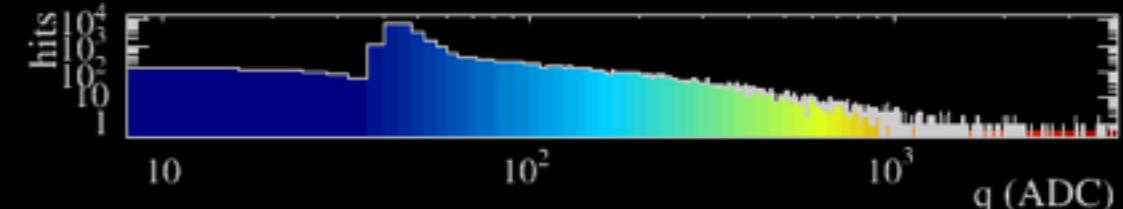
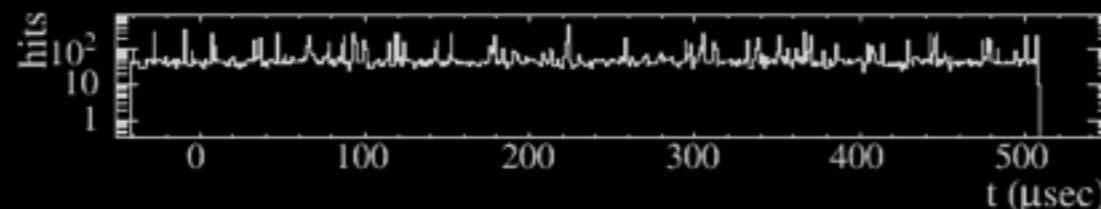
SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: 500 μ sec



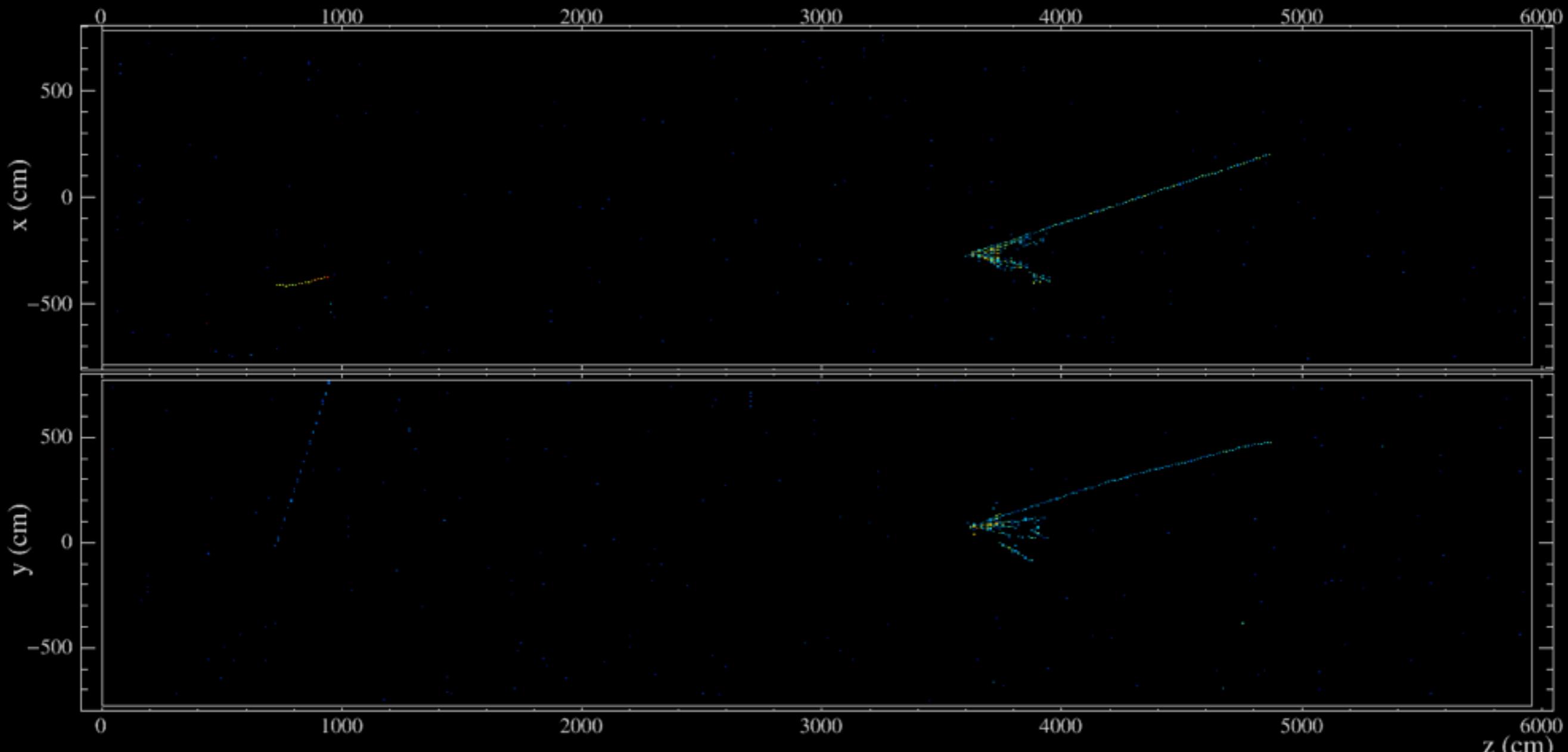
NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608



SEARCHING FOR NEUTRINOS IN FD

Beam spill trigger: zoom 10 μ sec



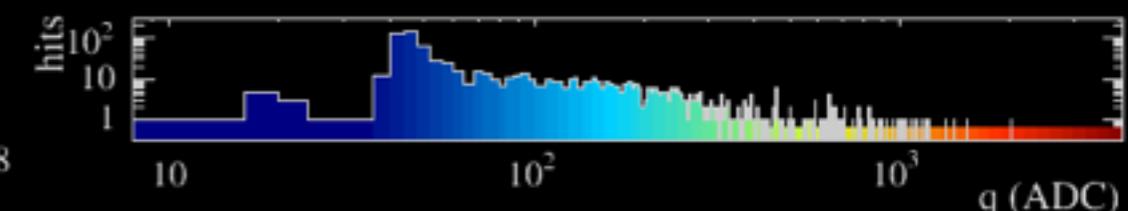
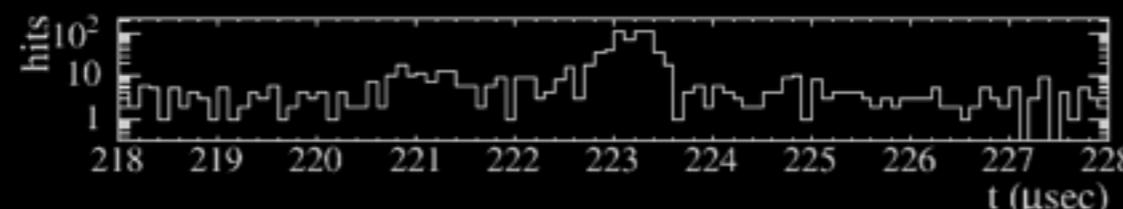
NOvA - FNAL E929

Run: 18620 / 13

Event: 178402 / --

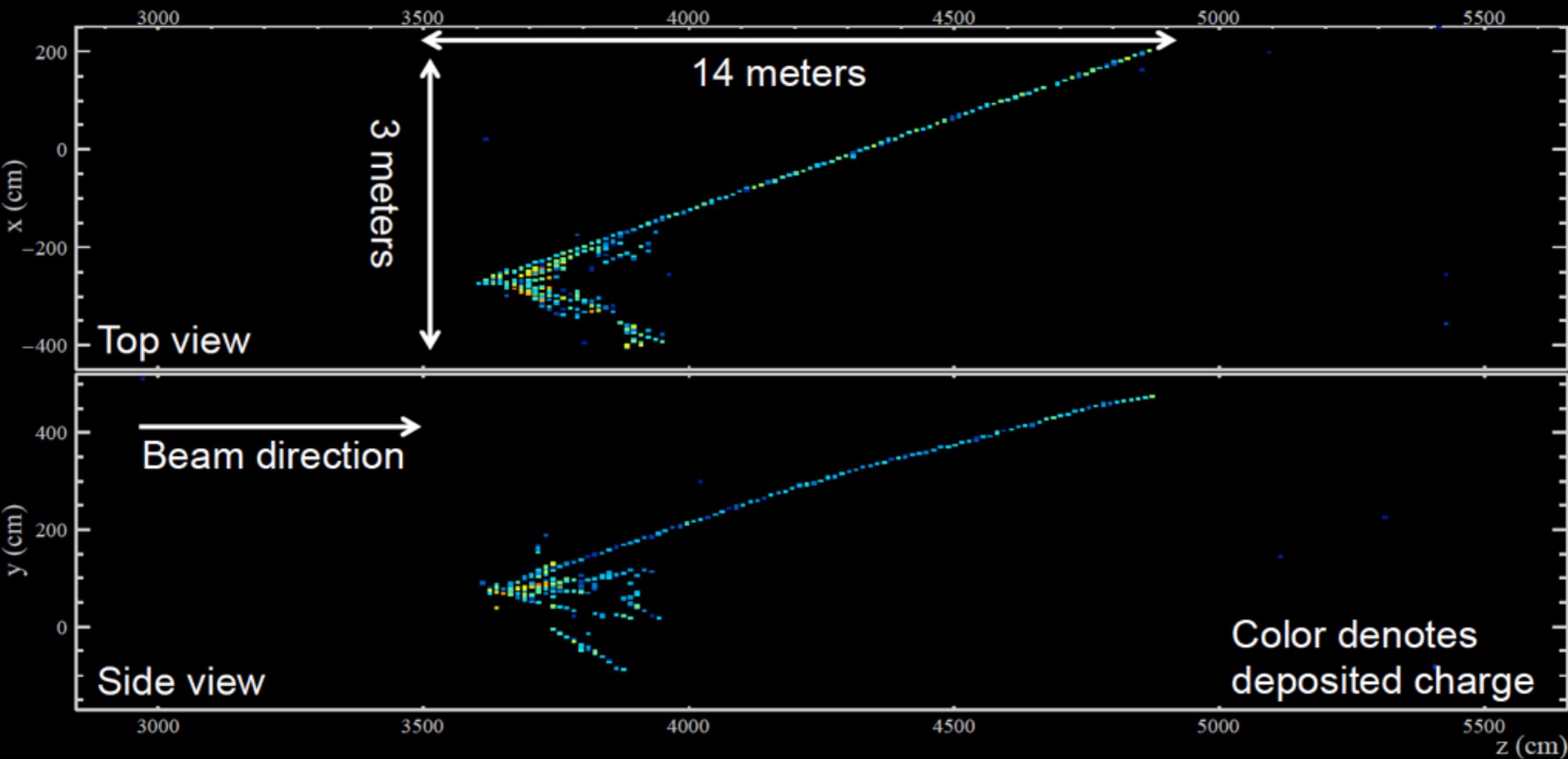
UTC Fri Jan 9, 2015

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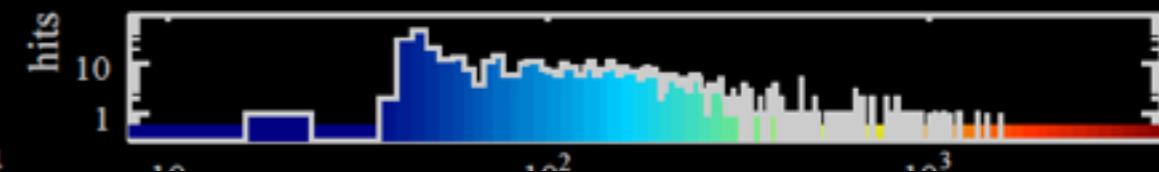
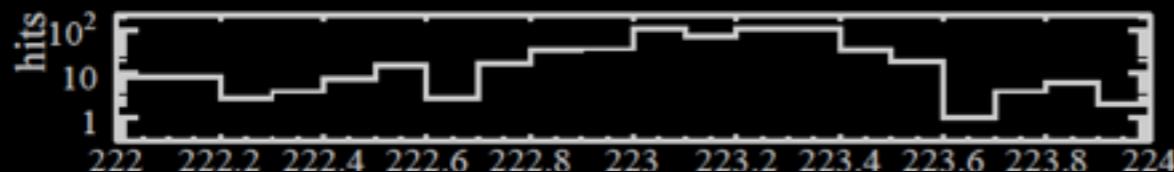


A MUON NEUTRINO CANDIDATE

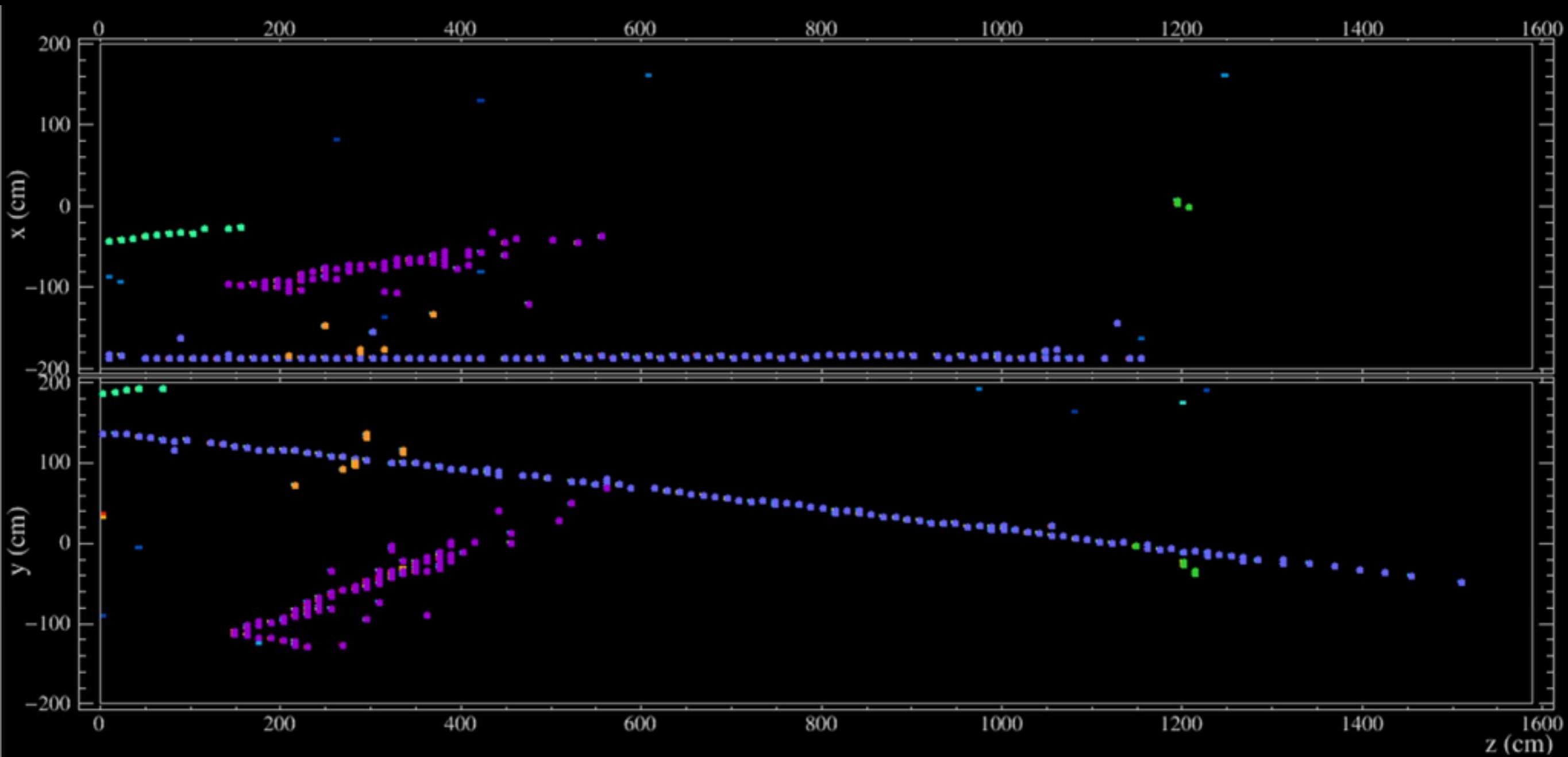
Zoomed in spatially



NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / -
UTC Fri Jan 9, 2015

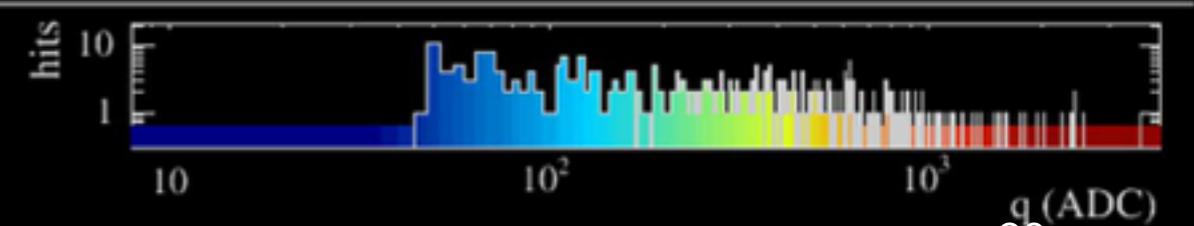
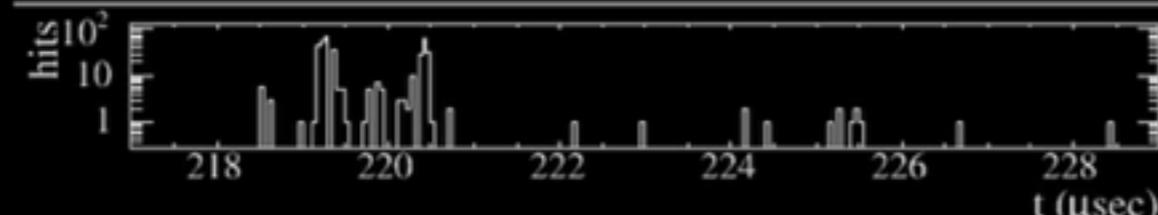


NEUTRINOS IN THE NEAR DETECTOR

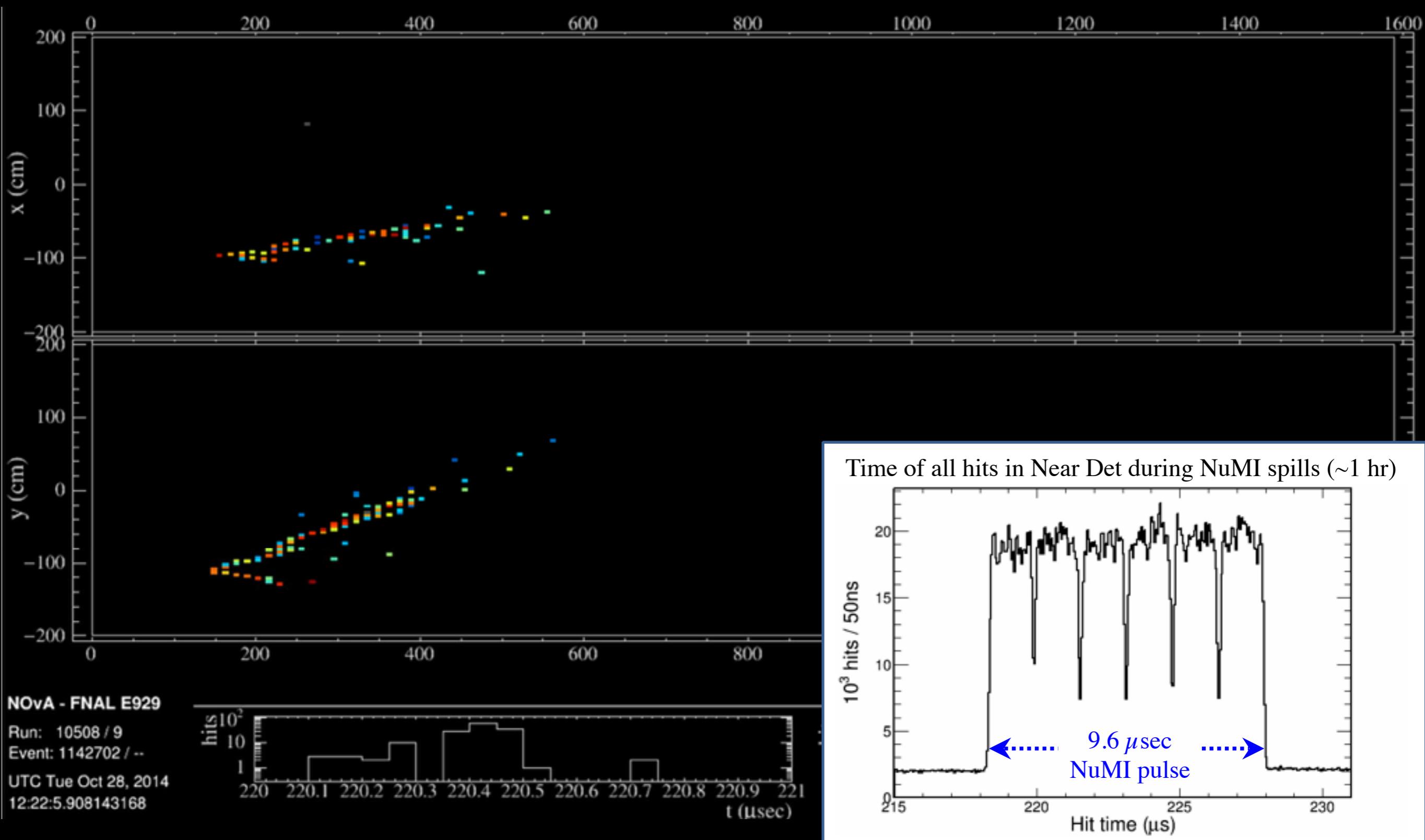


NOvA - FNAL E929

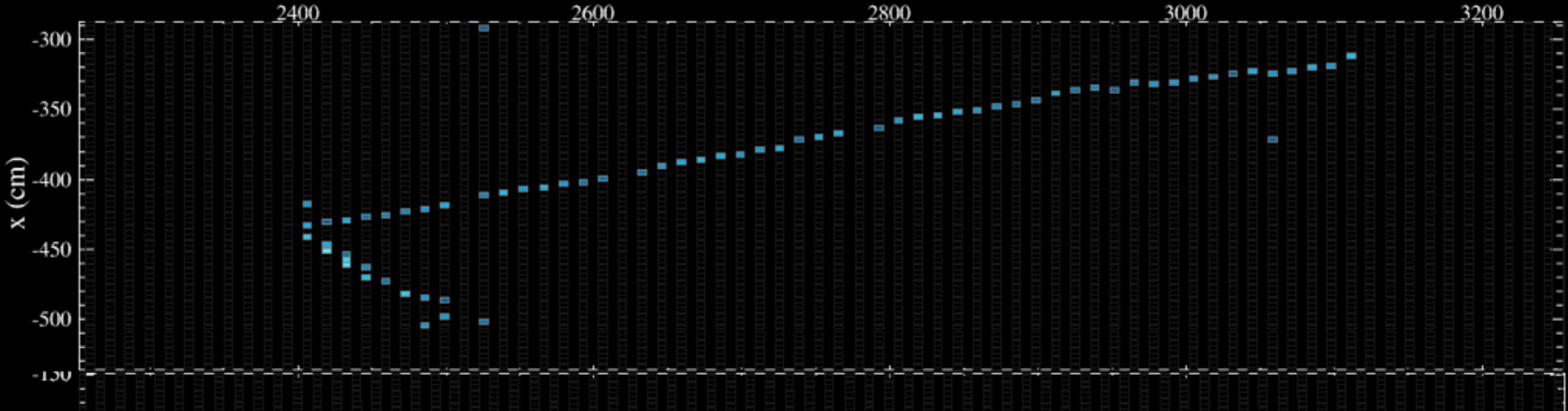
Run: 10508 / 9
Event: 1142702 / --
UTC Tue Oct 28, 2014
12:22:5.908143168



NEUTRINOS IN THE NEAR DETECTOR



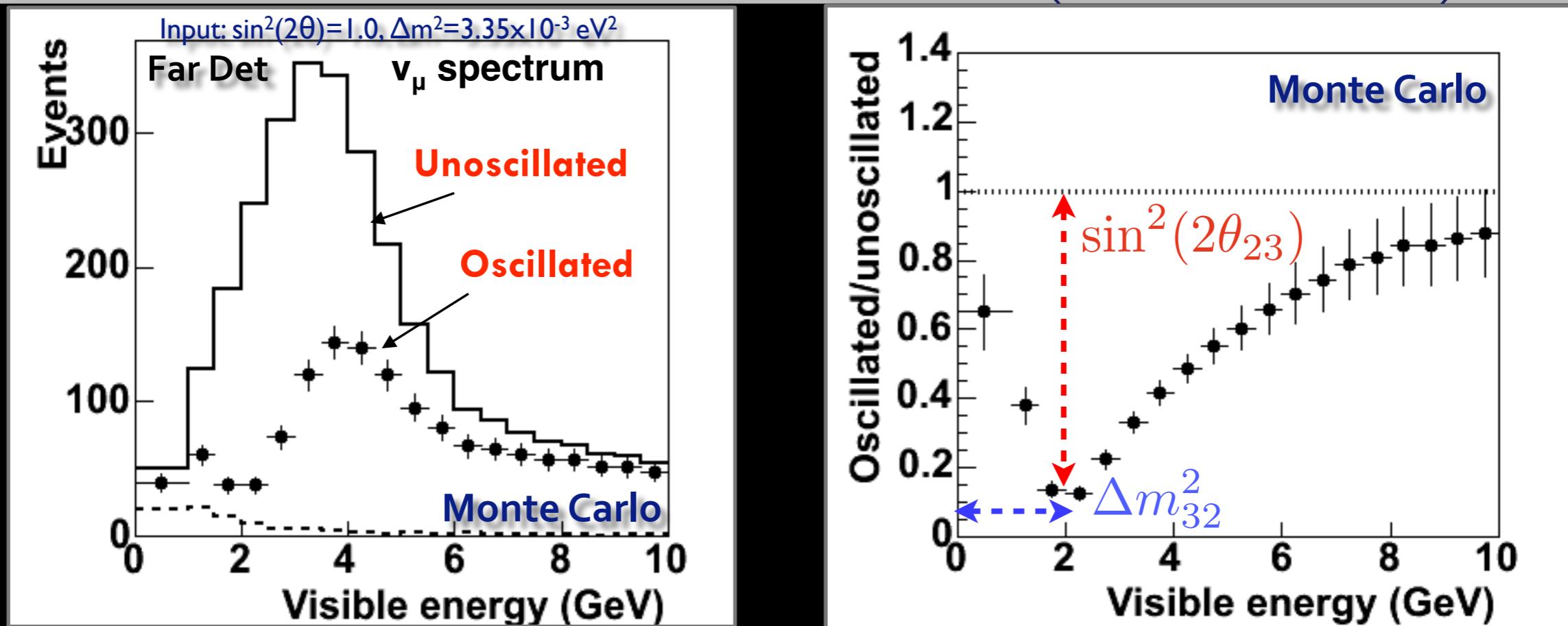
MUON NEUTRINO DISAPPEARANCE



MUON NEUTRINO DISAPPEARANCE

- In long-baseline experiments, we compare a prediction of the muon neutrino spectrum obtained from Near Detector data with a Far Detector measurement. Neutrino oscillations deplete rate and distort the energy spectrum.

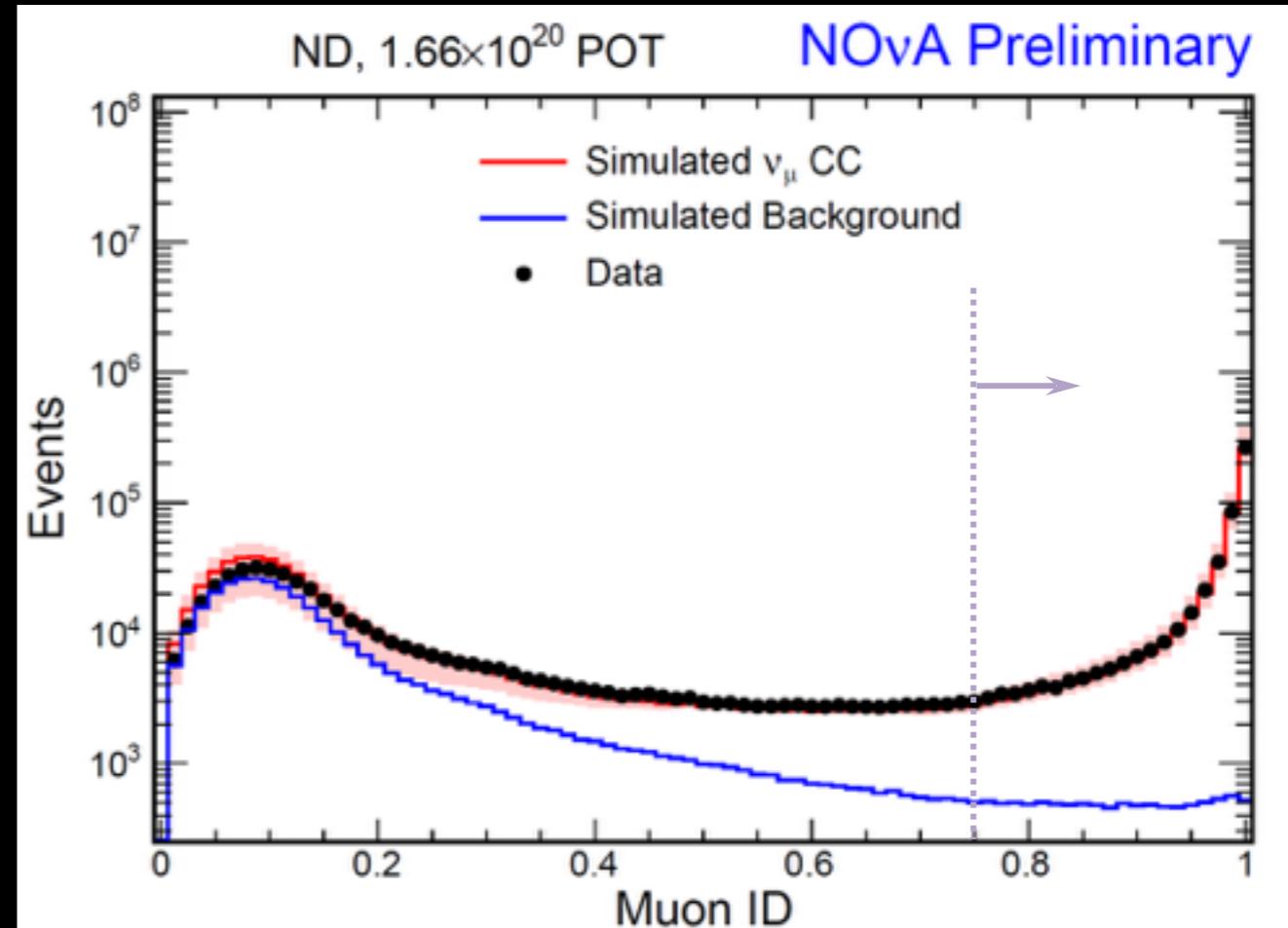
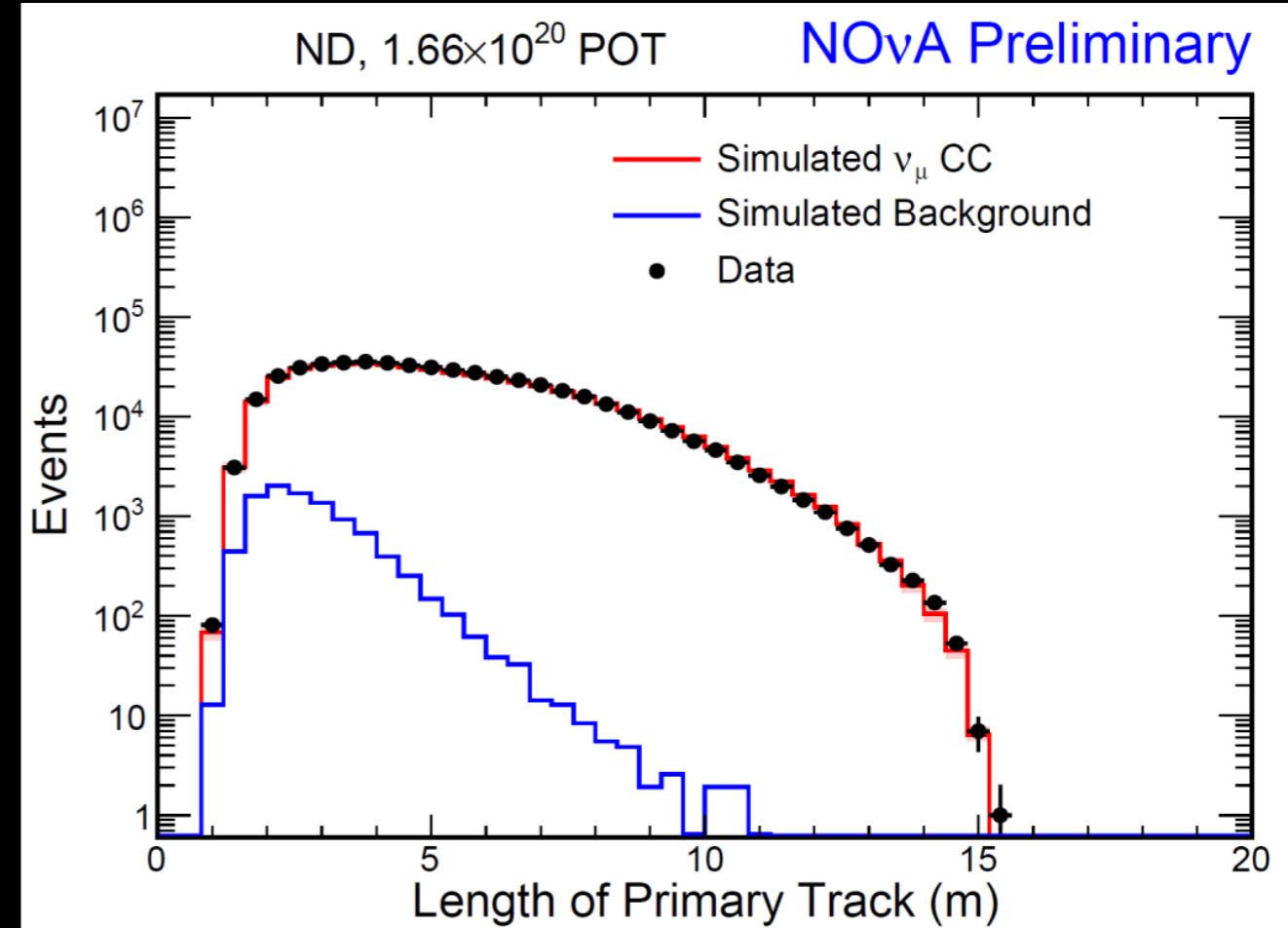
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2 \left(1.267 \Delta m_{32}^2 \frac{L}{E} \right)$$



IN AN OFF-AXIS EXPERIMENT NEAR THE OSCILLATION MAXIMUM
THE EFFECT IS EVEN MORE DRAMATIC

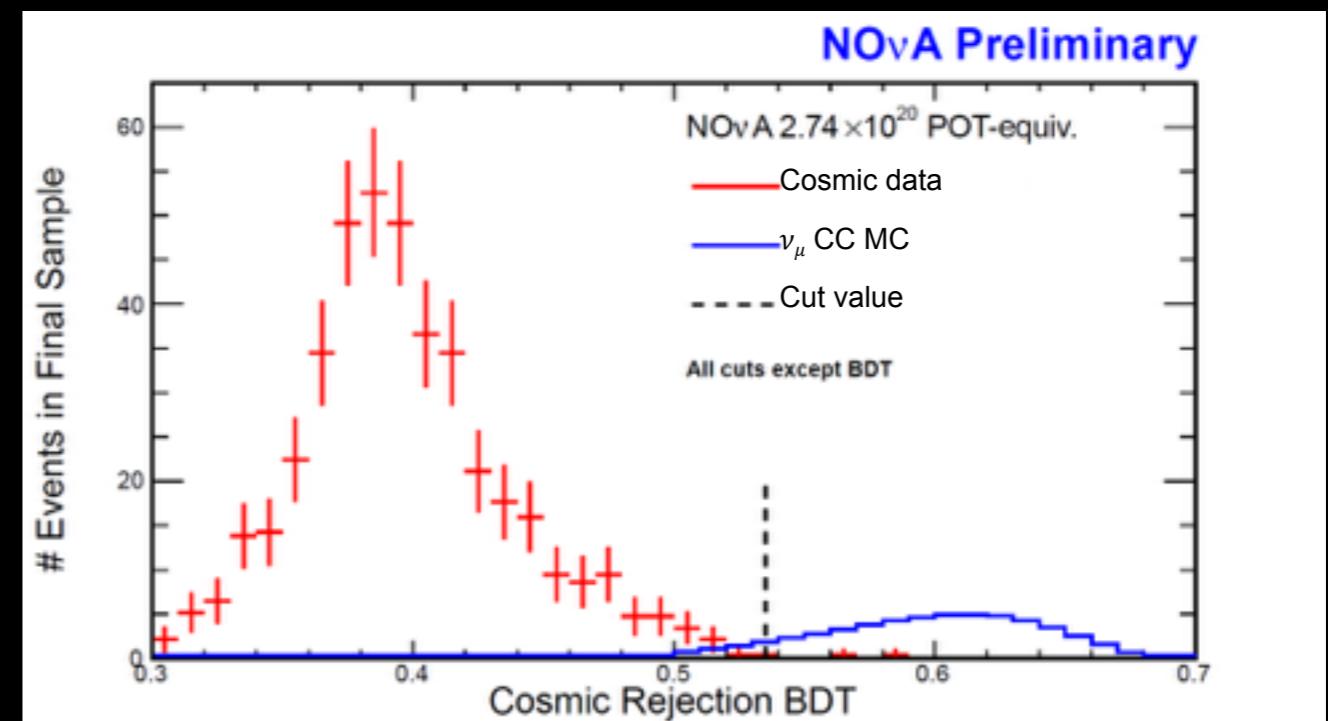
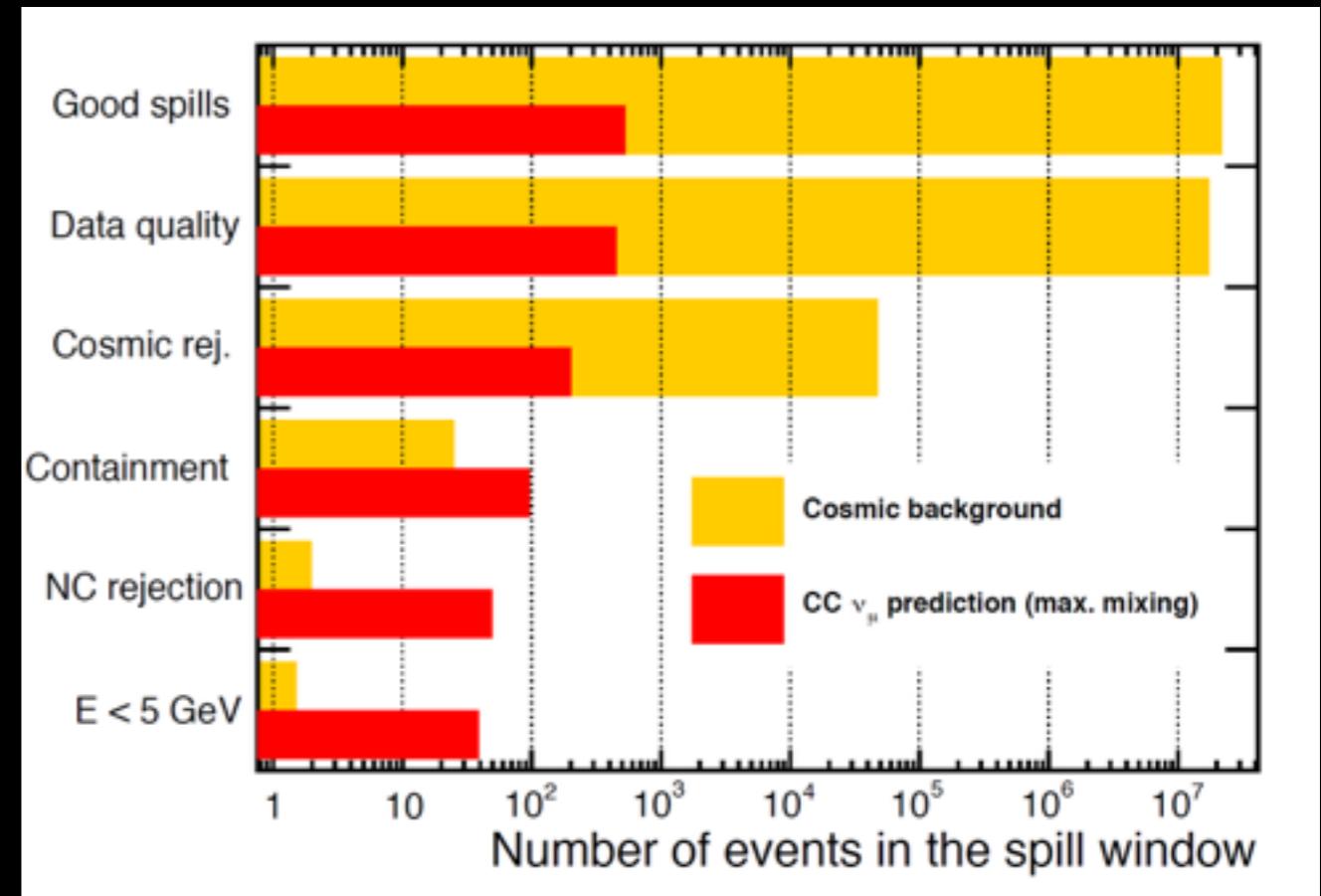
MUON NEUTRINO SELECTION

- We apply first basic containment cuts requiring no activity close to the wall of the detector.
- Excellent agreement of muon based data vs MC.
- We have developed a particle identification algorithm (k -nearest-neighbors) based on muon characteristics:
 - **track length**
 - dE/dx along the track
 - scattering along track
 - track-only plane fraction

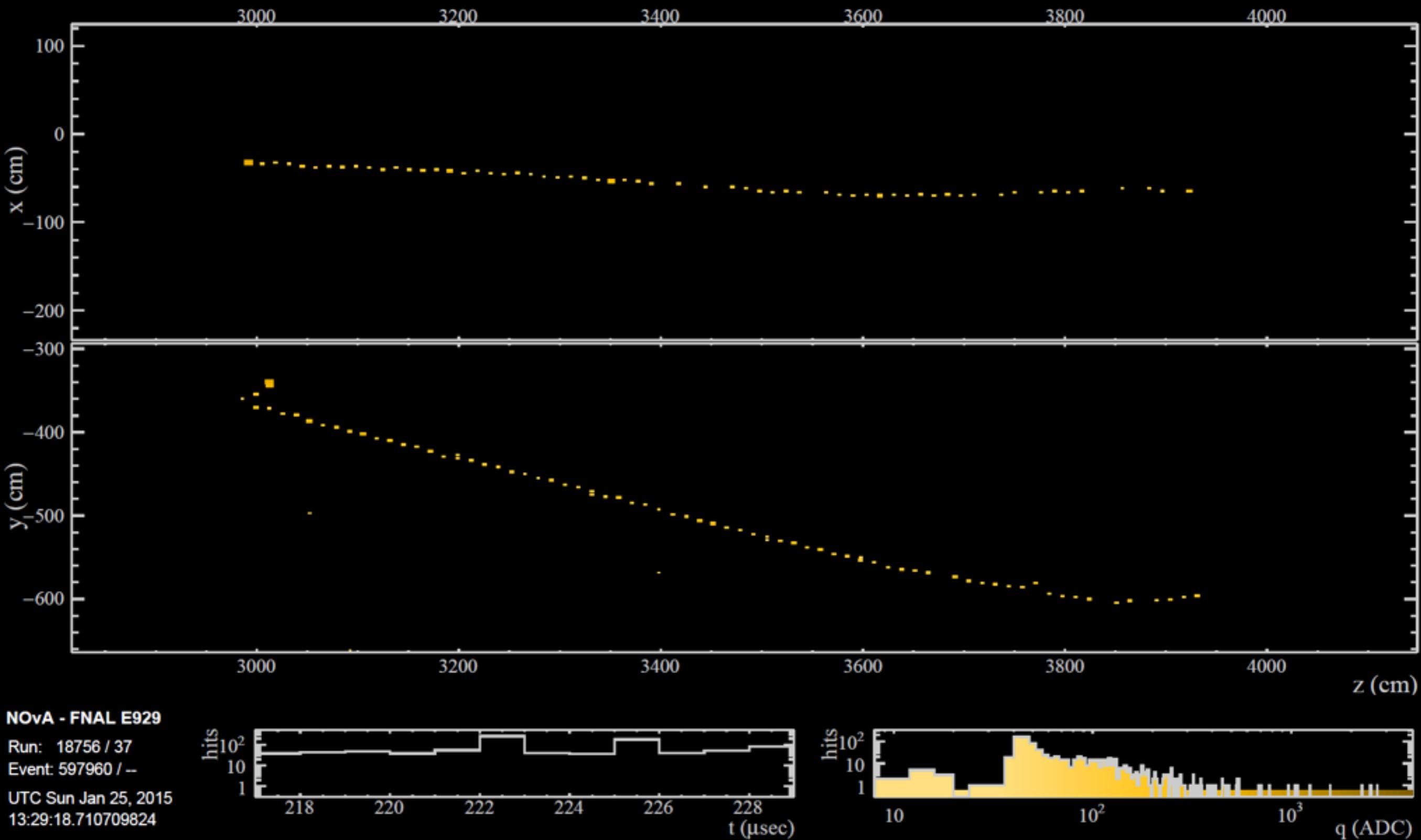


COSMIC REJECTION FOR MUON NEUTRINOS

- Final cosmic background rate is measured directly from data taken concurrently with beam spill by using the out-of-time window.
- Selecting a narrow window around the 9.6 μ sec spill gives a rejection factor of 10^5 .
- For the cosmic rejection of the muon neutrino disappearance analysis, we use a boosted decision tree algorithm based on:
 - Reconstructed track direction, position, and length; and energy and number of hits in event.
 - Event topology gives an additional factor of 10^7 rejection.

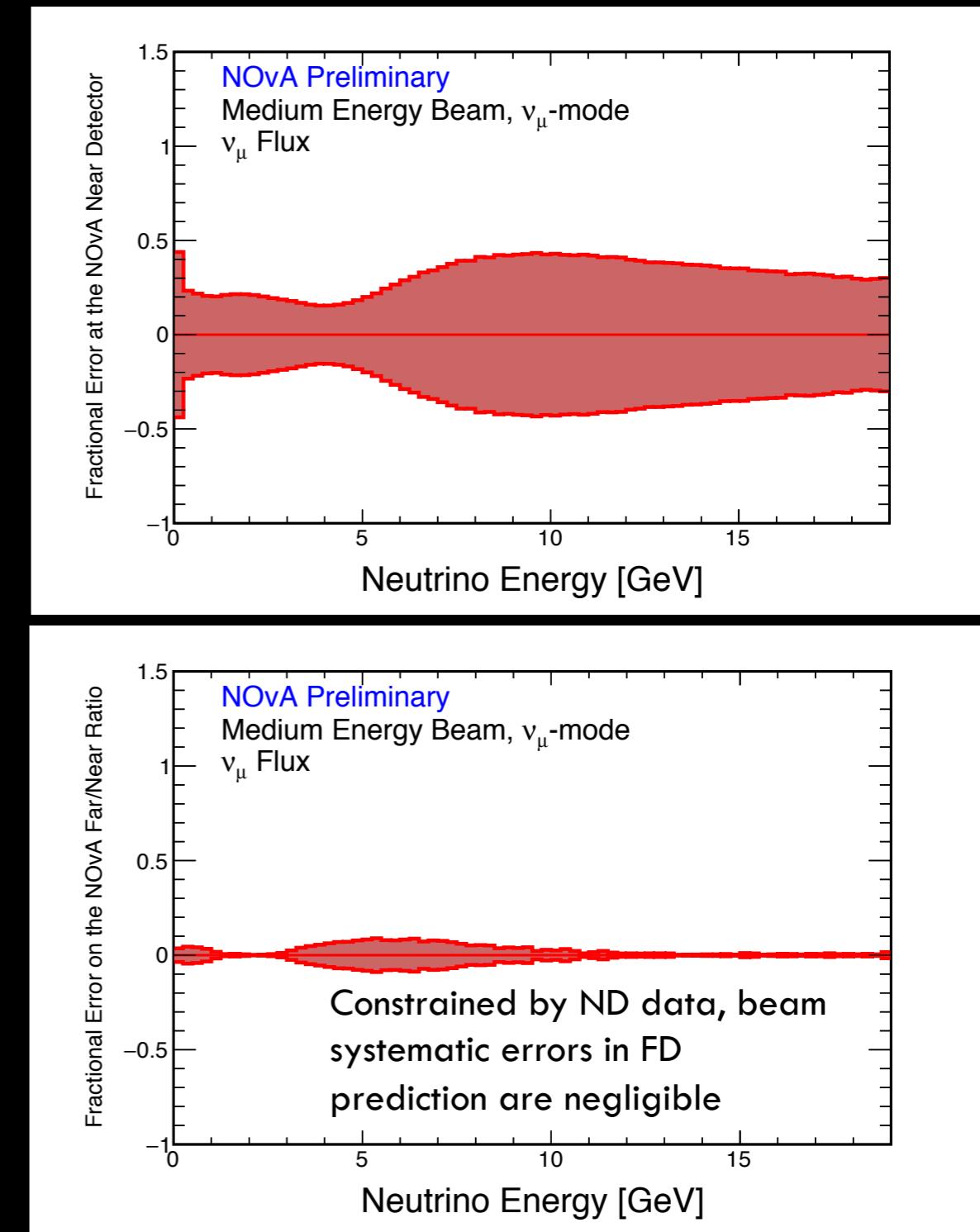
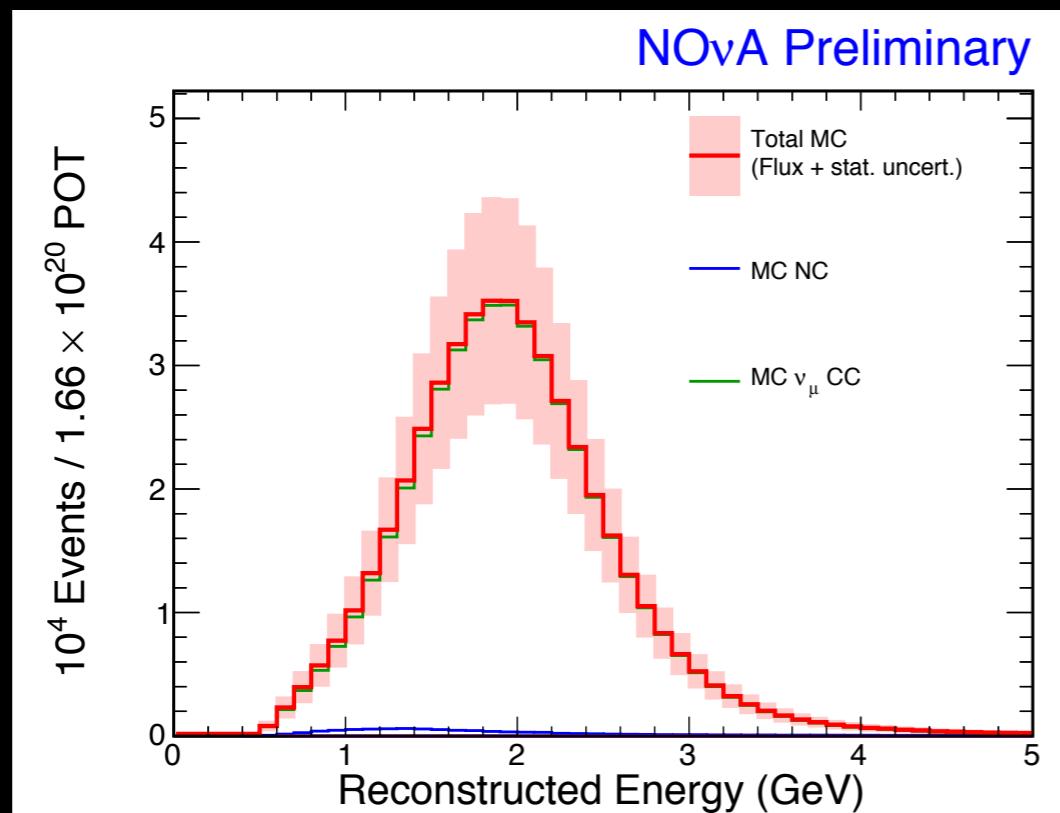


MUON NEUTRINO CANDIDATE



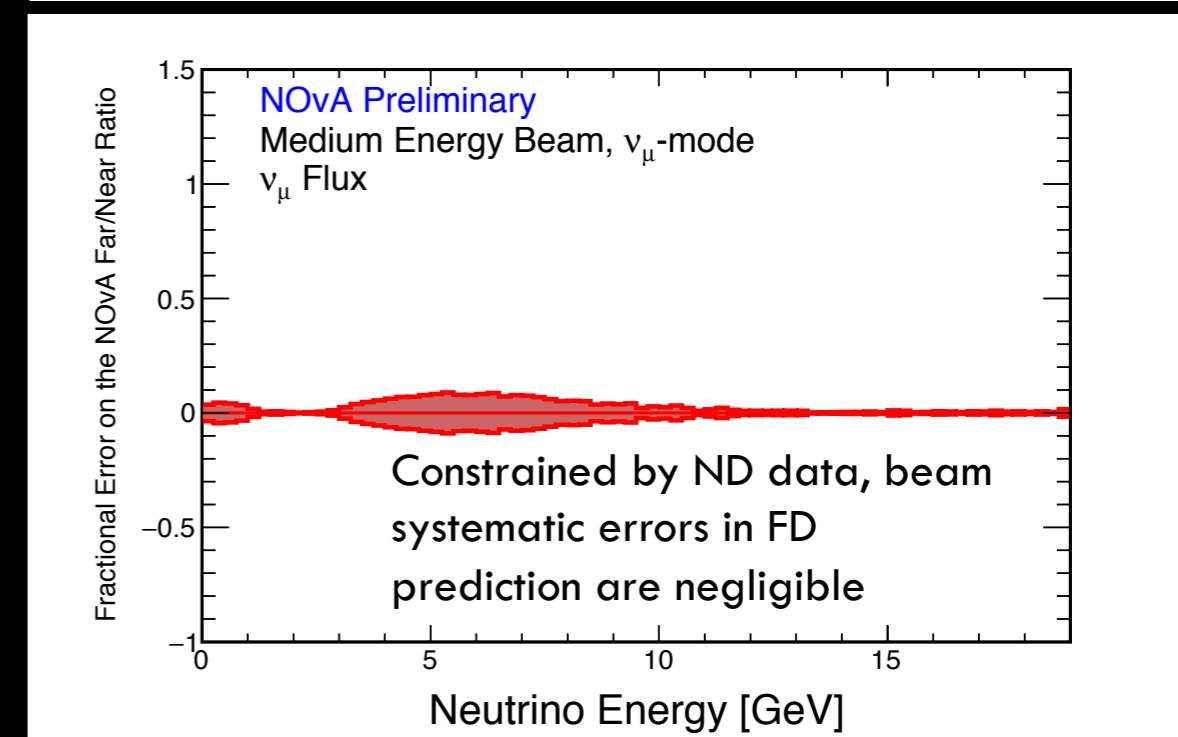
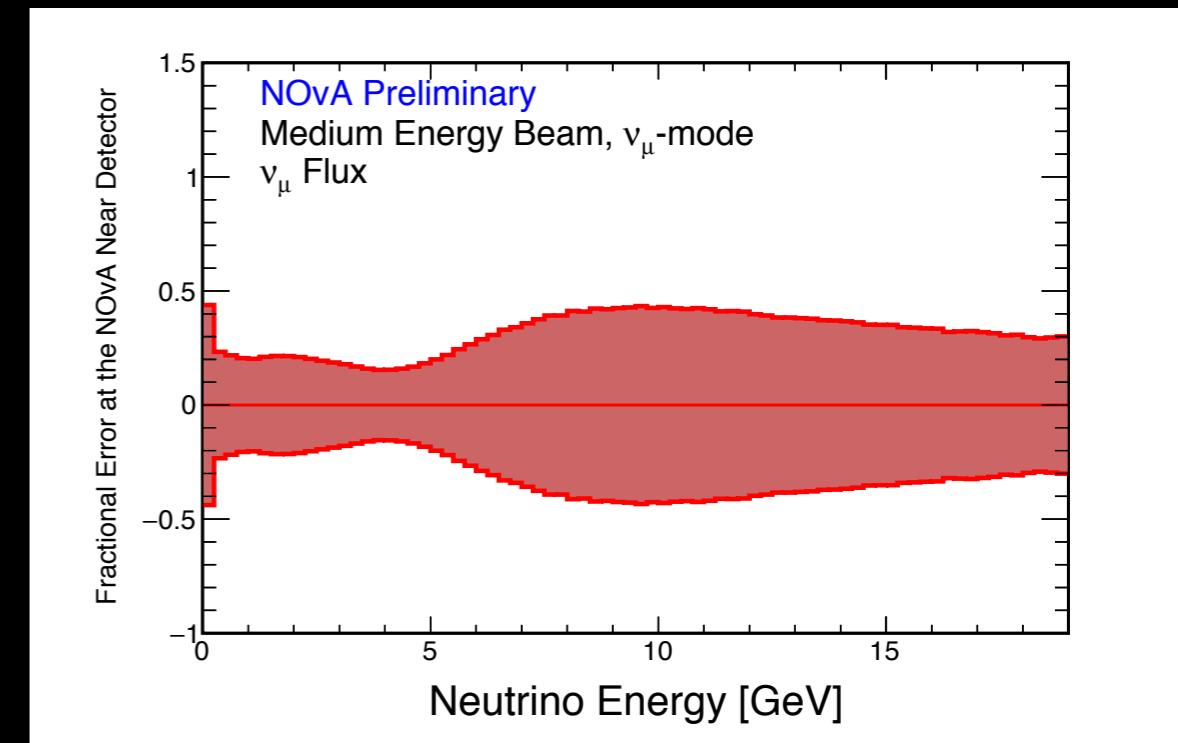
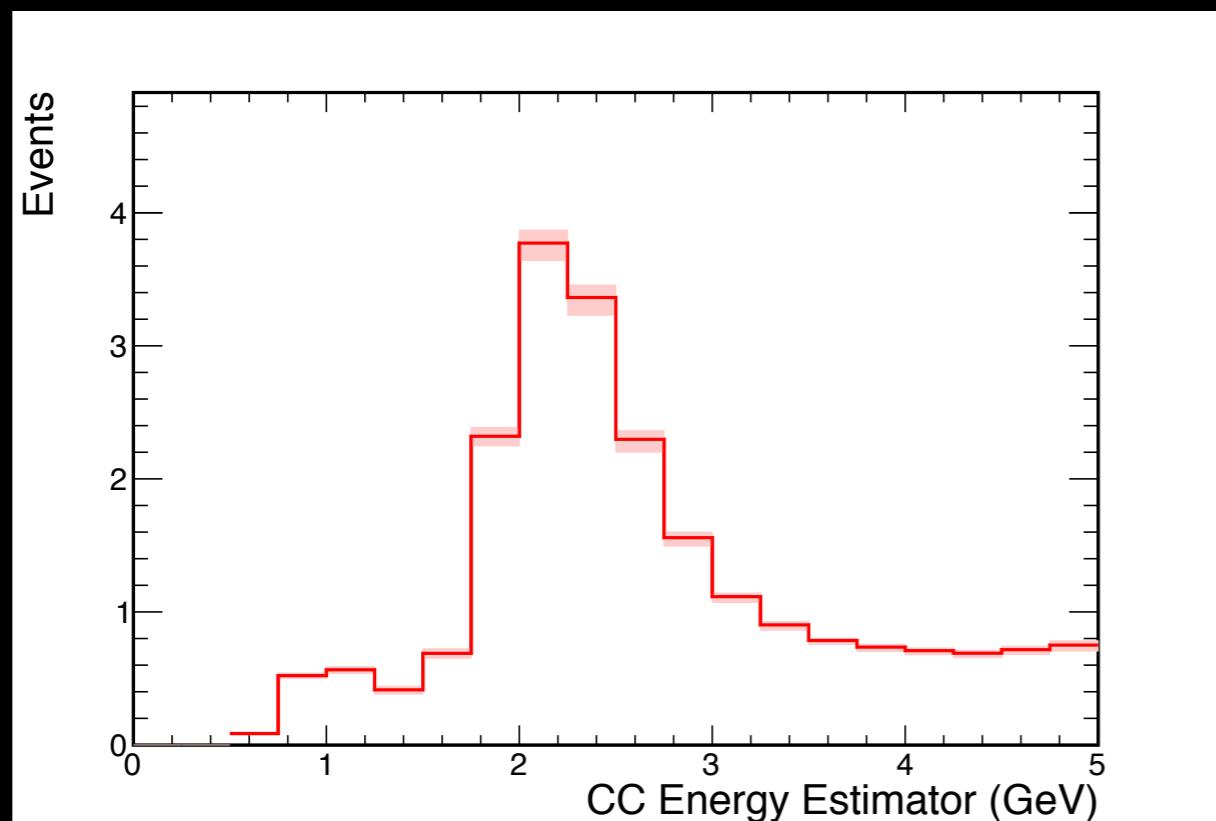
SYSTEMATIC UNCERTAINTIES

- The two **functionally-identical** detector technique in NOvA largely reduces several uncertainties typical of accelerator neutrino experiments:
 - Hadron production uncertainty in the neutrino target and beam line focusing errors cause +/-20% changes in normalization, but peak energy shifts by less than 1.5%.
 - MIPP hadron production data and MINERvA flux measurement promise to reduce normalization uncertainty by more than a factor of 2.



SYSTEMATIC UNCERTAINTIES

- The two **functionally-identical** detector technique in NOvA largely reduces several uncertainties typical of accelerator neutrino experiments:
 - Neutrino interaction uncertainties also cancel in the extrapolation, leaving a residual 3.5% change in number of events. Largest contributions from modifying axial mass in QE and RES cross section parameterization
 - ND beam peak moves by less than 1%.



SYSTEMATIC UNCERTAINTIES TO THE MUON NEUTRINO DISAPPEARANCE MEASUREMENT

Source	$\delta(\sin^2\theta_{23})$ ($\pm\%$)	$\delta(\Delta m^2)$ ($\pm\%$)
Absolute Calorimetric Energy Calibration [$\pm 22\%$]	7.7	3.1
Relative Calorimetric Energy Calibration [$\pm 5.4\%$]	3.7	0.8
Cross Sections and FSI [$\pm(15-25)\%$]	0.6	0.7
NC and CC Backgrounds	3.2	0.7
Detector Response	1.3	0.7
Flux [$\pm 21\%$]	1.6	0.4
Exposure [$<\pm 2\%$]	0.3	0.2
Oscillation Parameters	2.1	2.2
Total Systematic	9.2	4.1
Statistical	19	5.0

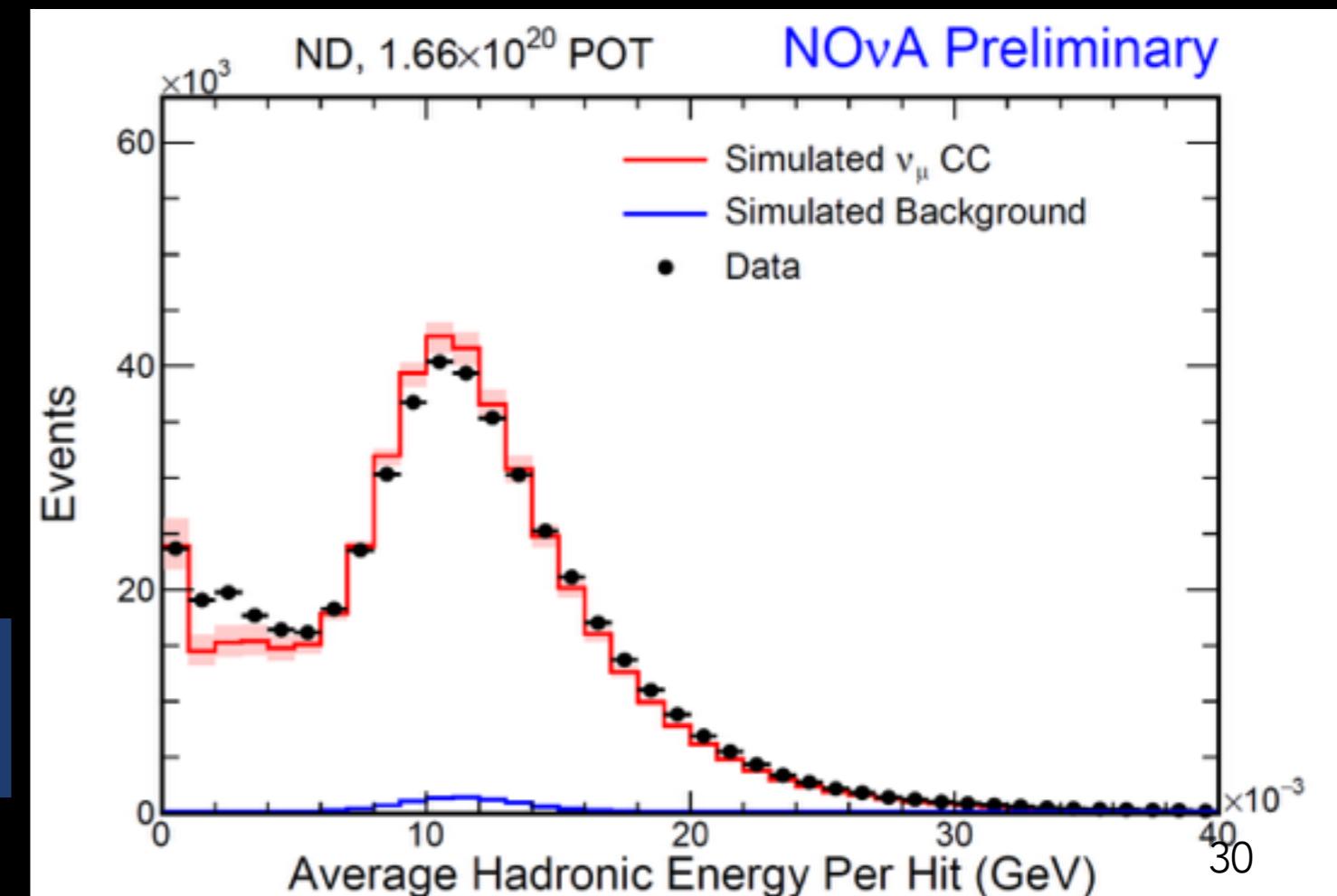
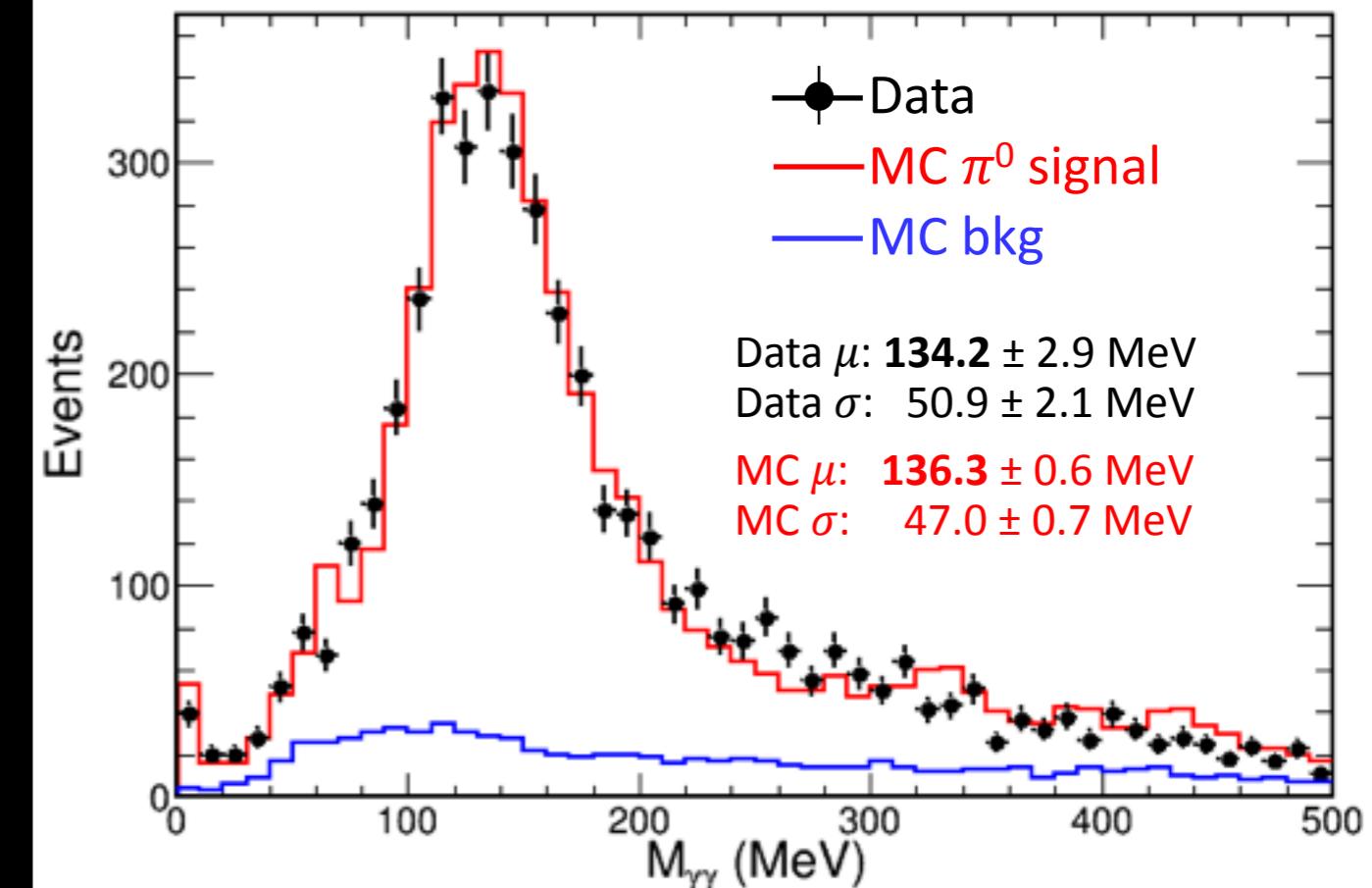
- While many uncertainties largely cancel, the two dominant systematics are absolute and relative calorimetric energy, dominated by the understanding of the hadronic energy.

CALIBRATION AND THE ABSOLUTE ENERGY SCALE

- Stopping muons provide a standard candle for setting absolute energy scale.
- Several samples demonstrate successful energy scale calibration:
 - cosmic μ dE/dx [~vertical]
 - beam μ dE/dx [~horizontal]
 - Michel e- spectrum
 - π^0 mass
 - hadronic shower energy/hit

ALL SAMPLES AGREE
WITHIN $\pm 5\%$

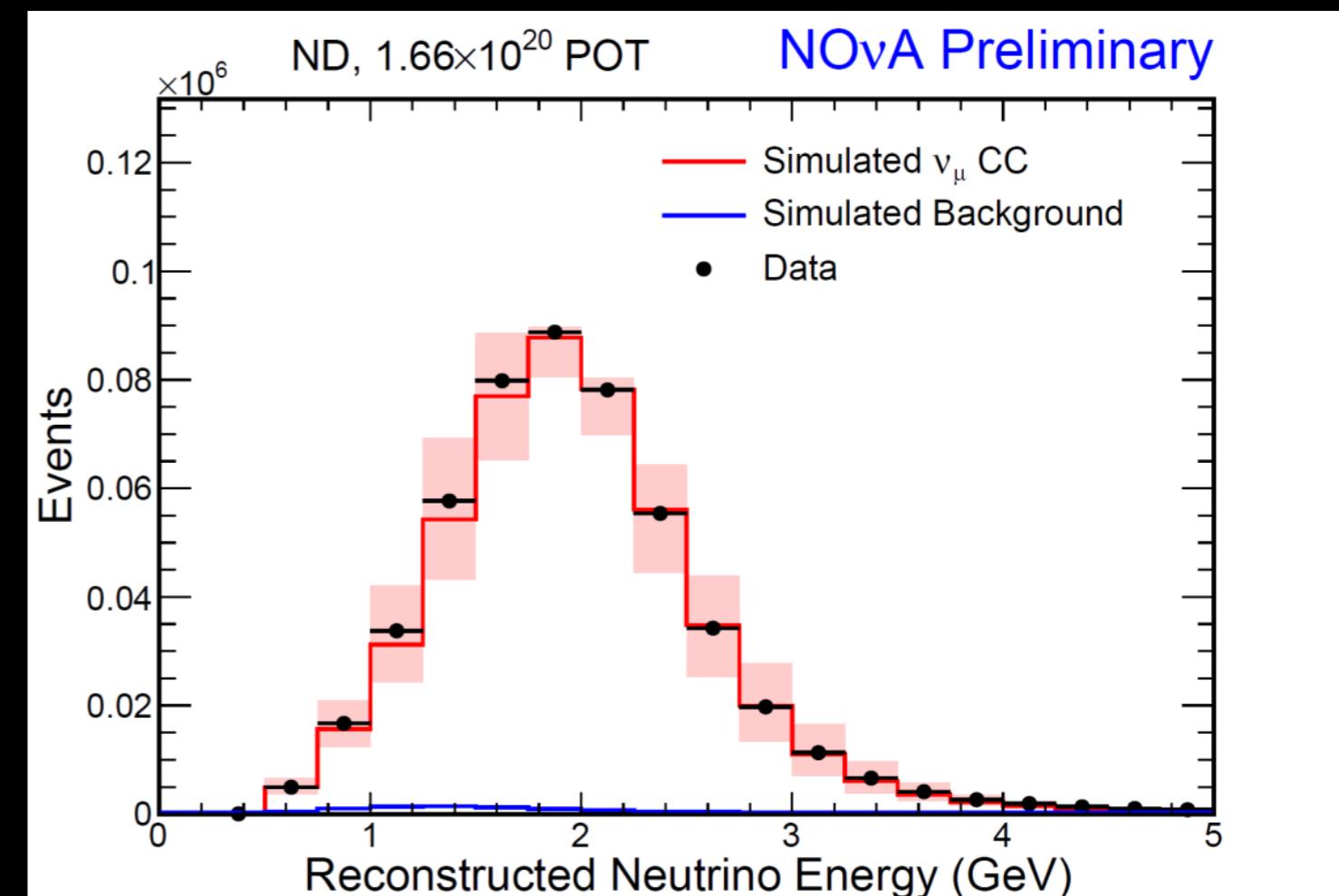
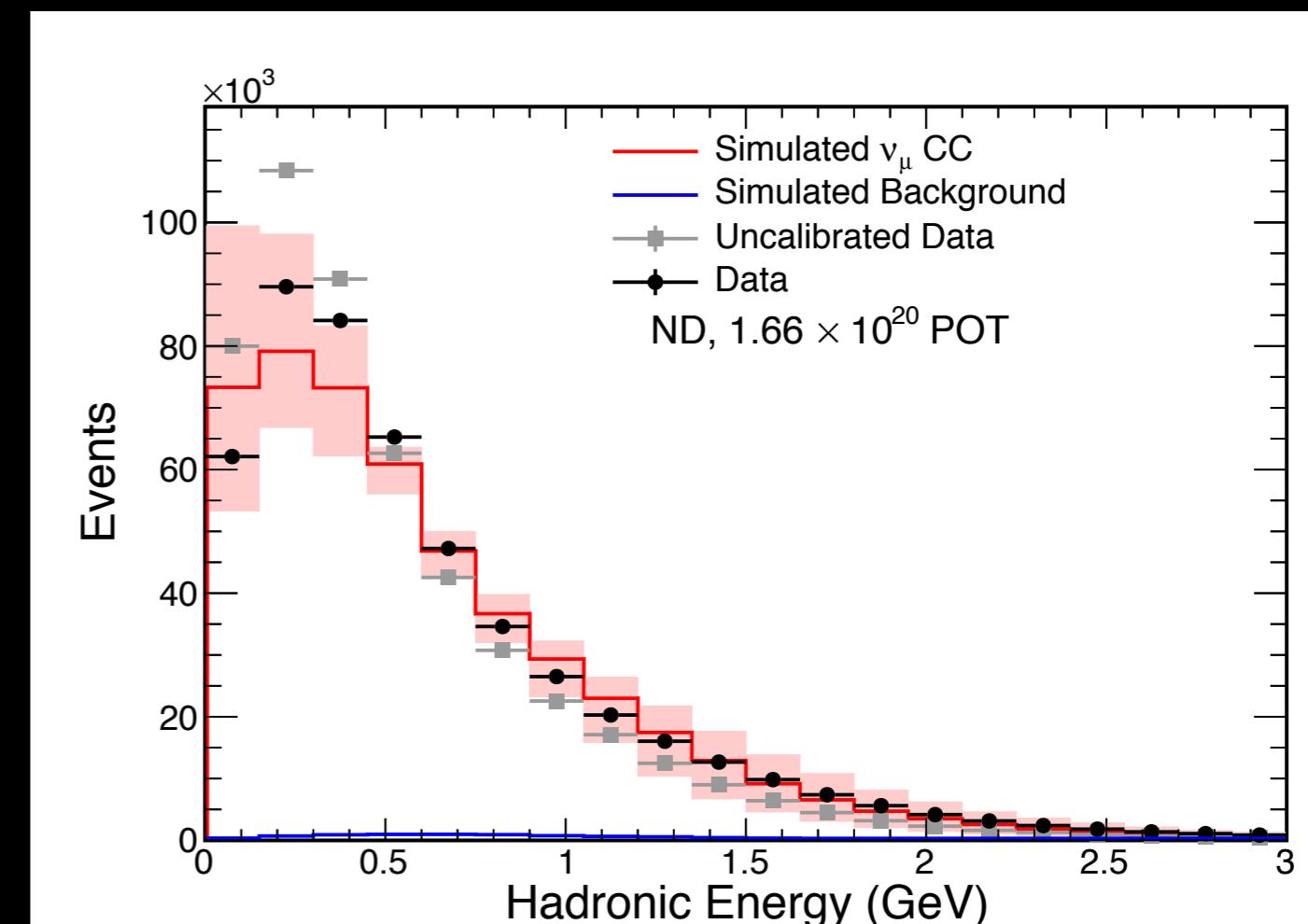
NOvA Preliminary



HADRONIC ENERGY SYSTEMATIC

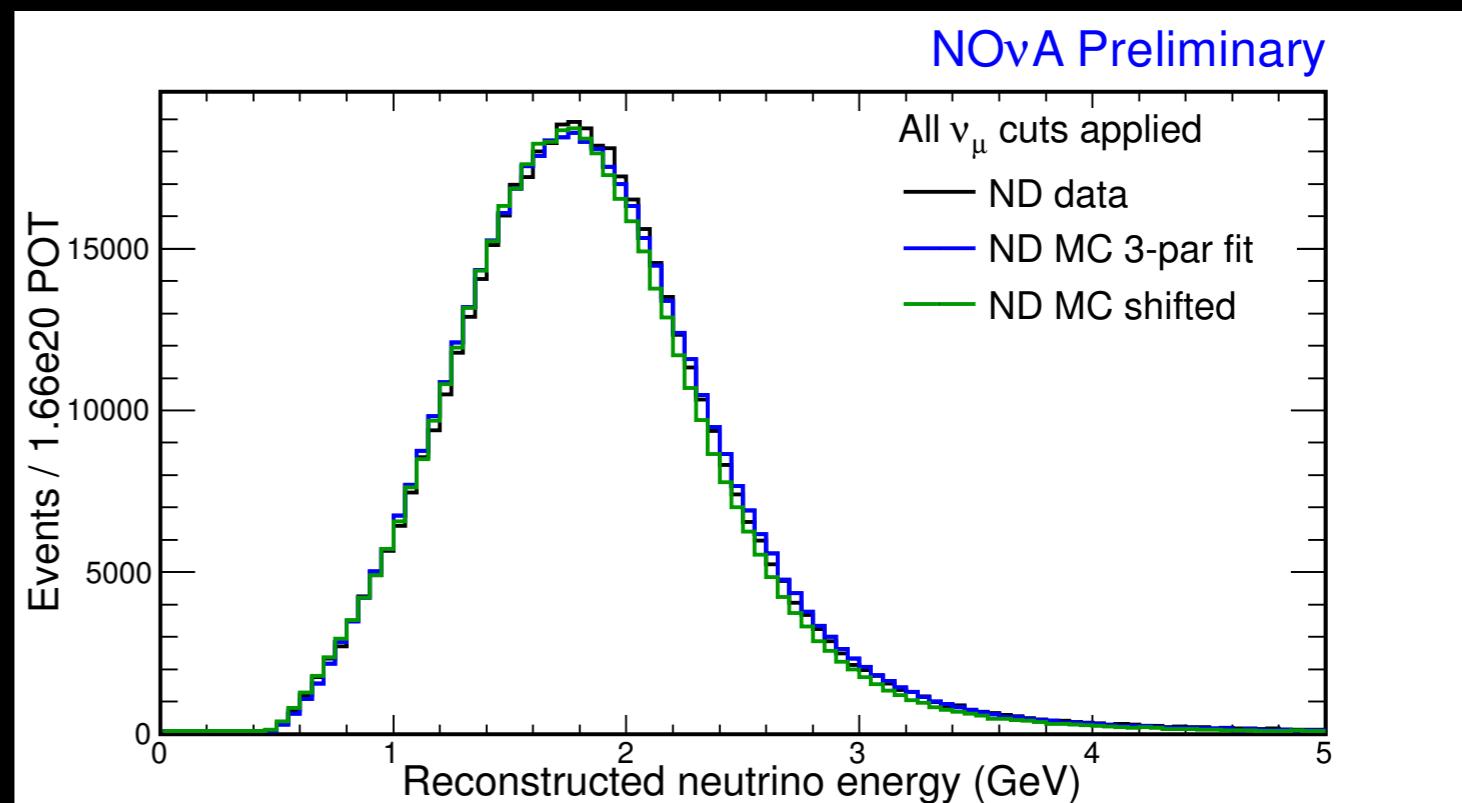
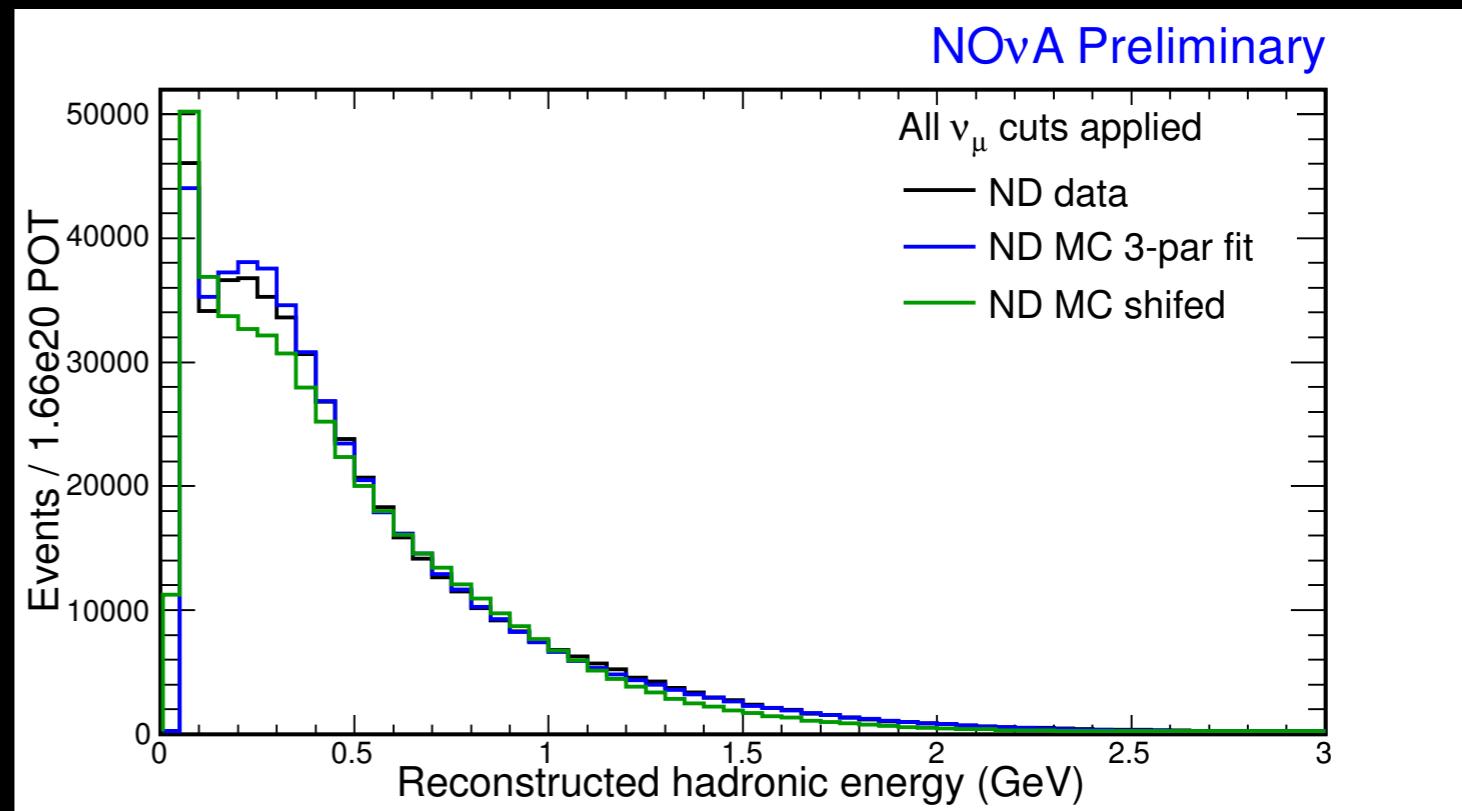
- Data vs MC show good agreement for muon neutrino selected events since muons are very well described by our MC.
- However, Monte Carlo has 21% more energy in the hadron system than seen in data.
- The hadron energy is thus recalibrated such that the total energy peak of the data matches the MC.
- This results in 6% overall neutrino energy scale uncertainty.

ND DATA IS USED TO PRODUCE A DATA DRIVEN PREDICTION IN THE FD

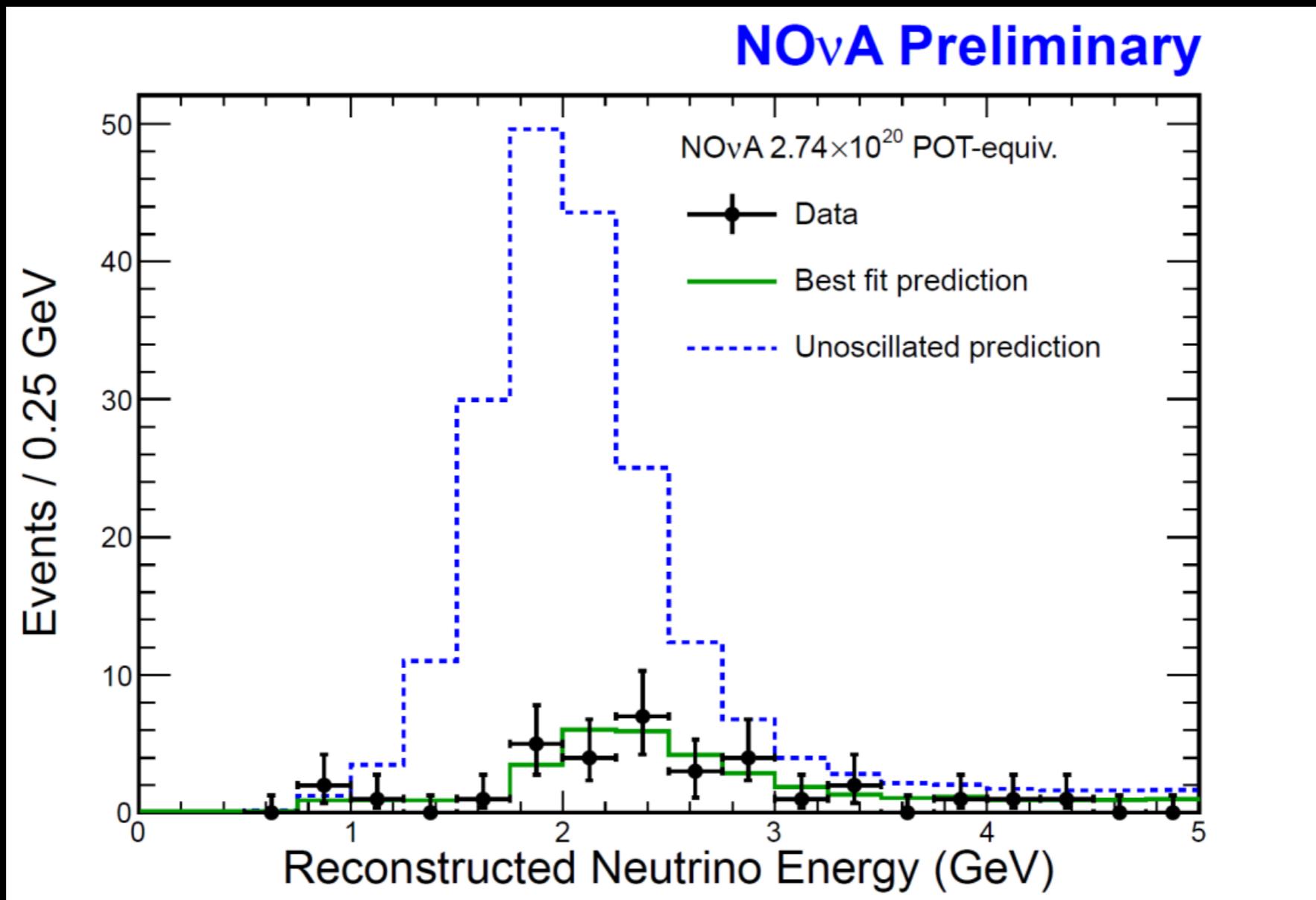


HADRONIC ENERGY SYSTEMATIC

- Additionally implies a detector-to-detector relative energy systematic
- We assume different models to correct hadronic energy.
 - Allow energy scale and normalization of each process type (QE/RES/DIS) to vary.
 - 2% difference in hadronic energy scale between two correction methods used as systematic.



MUON NEUTRINO SELECTED SPECTRUM



- We expect 201 events before oscillations.
- We observe 33 events.

MUON NEUTRINO DISAPPEARANCE RESULTS

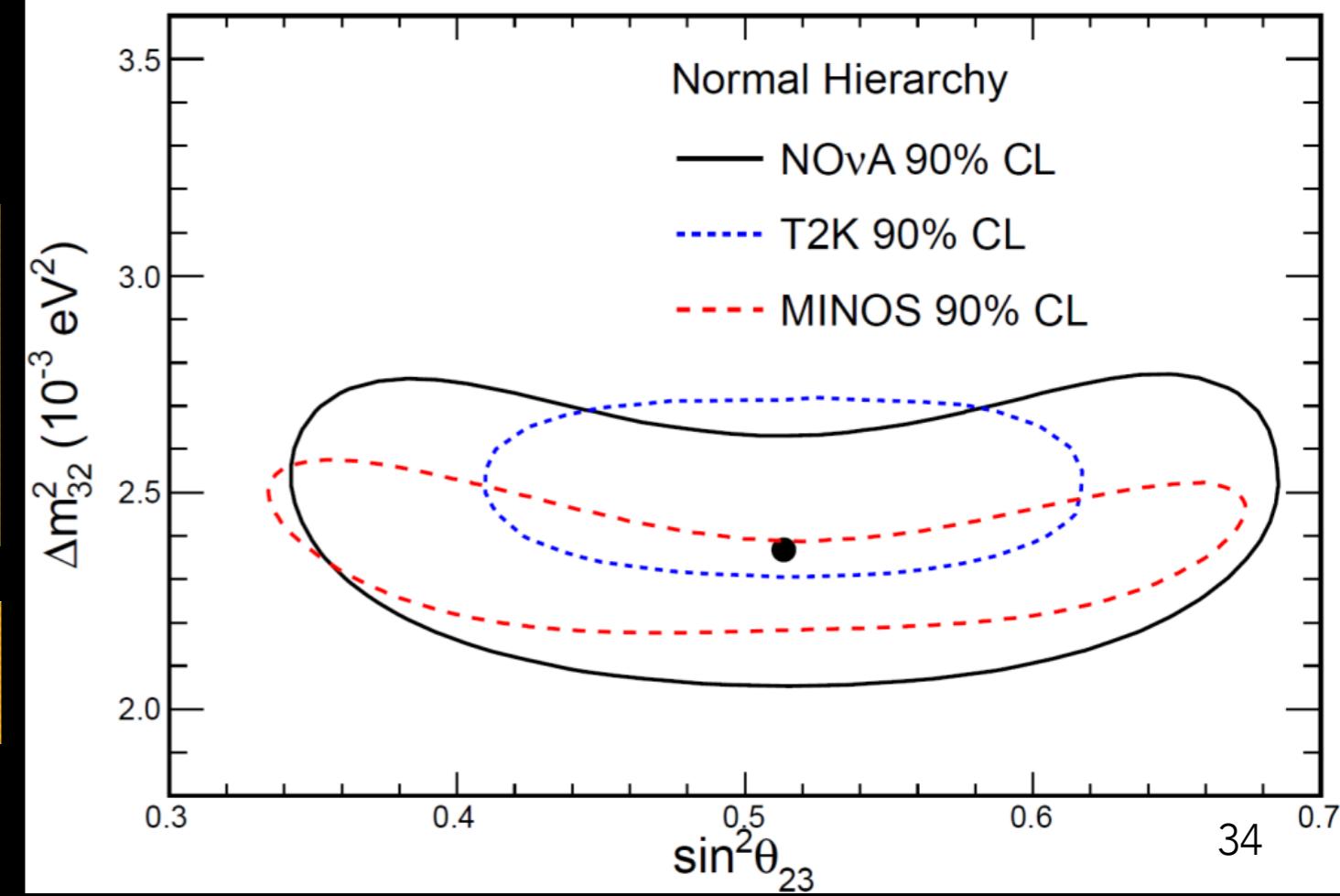
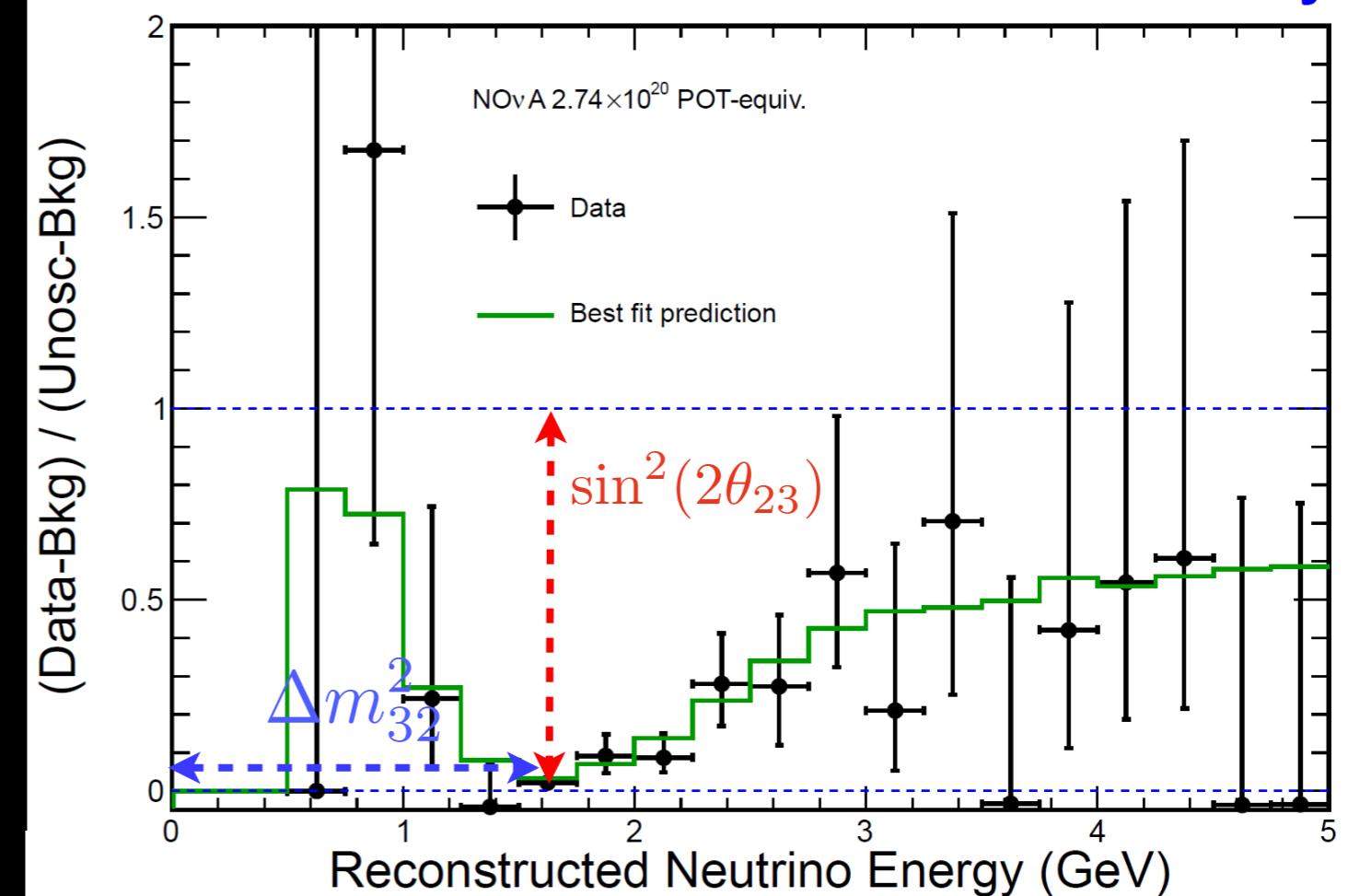
- The spectrum is matched **beautifully** by the oscillation fit.
- Largest systematic is hadronic neutrino energy.
- Parameter measurements:

$$\Delta m_{32}^2 = +2.37^{+0.16}_{-0.15} \text{ [normal ordering]}$$

$$\Delta m_{32}^2 = -2.40^{+0.14}_{-0.17} \text{ [inverted ordering]}$$

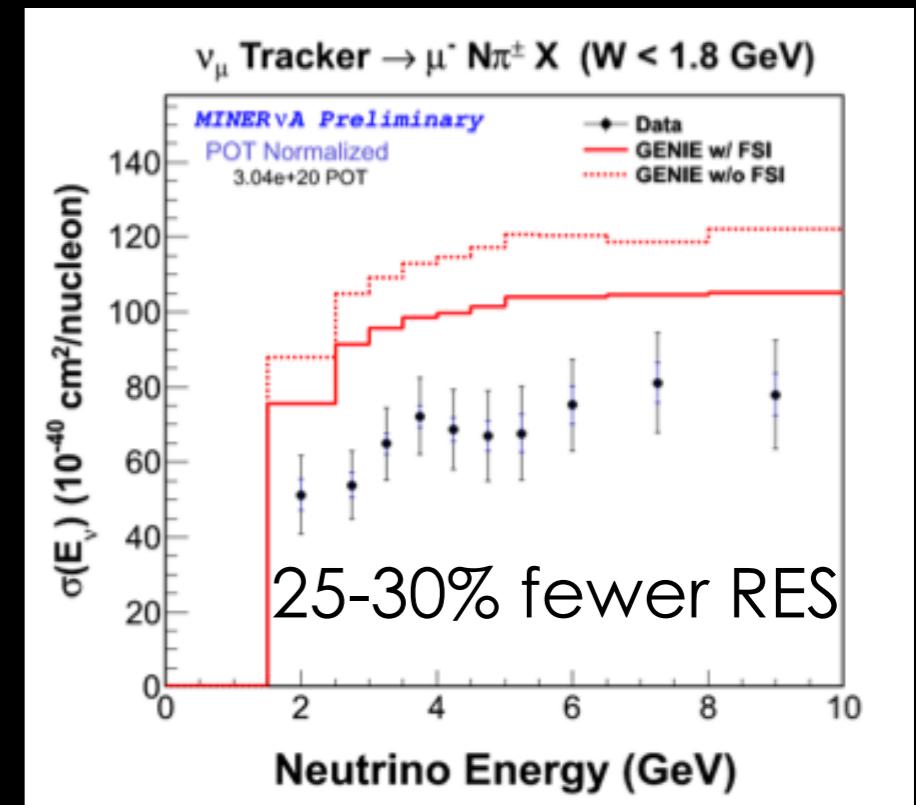
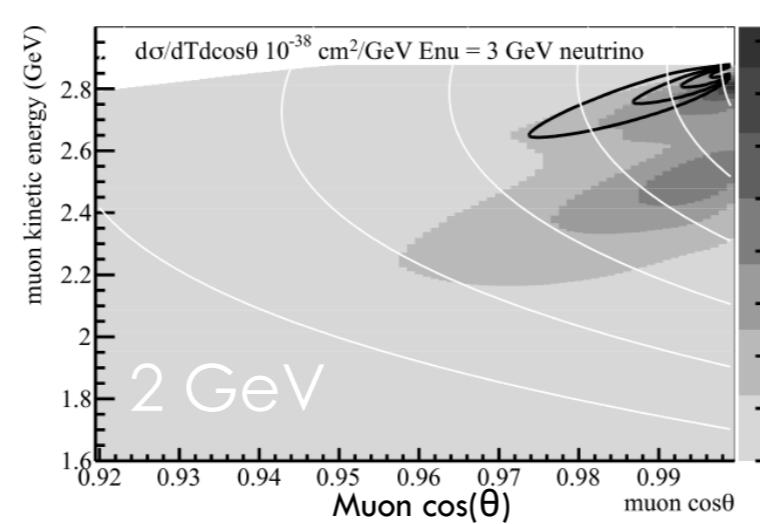
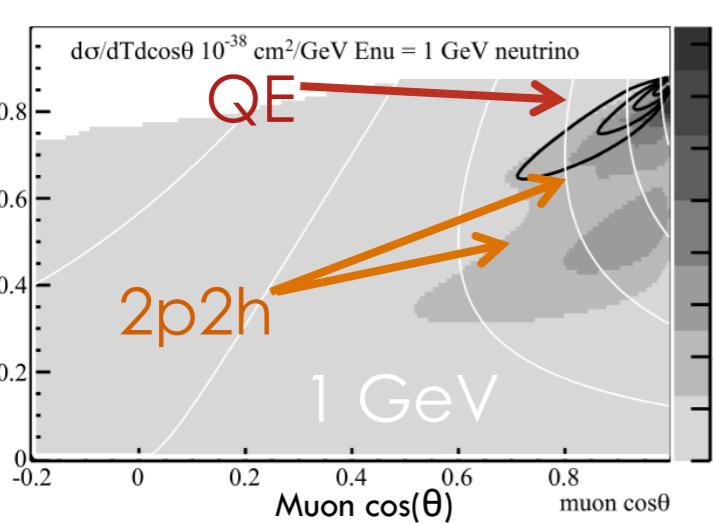
$$\sin^2 \theta_{23} = 0.51 \pm 0.10$$

COMPELLING MEASUREMENT
WITH 7.6% OF NOMINAL EXPOSURE

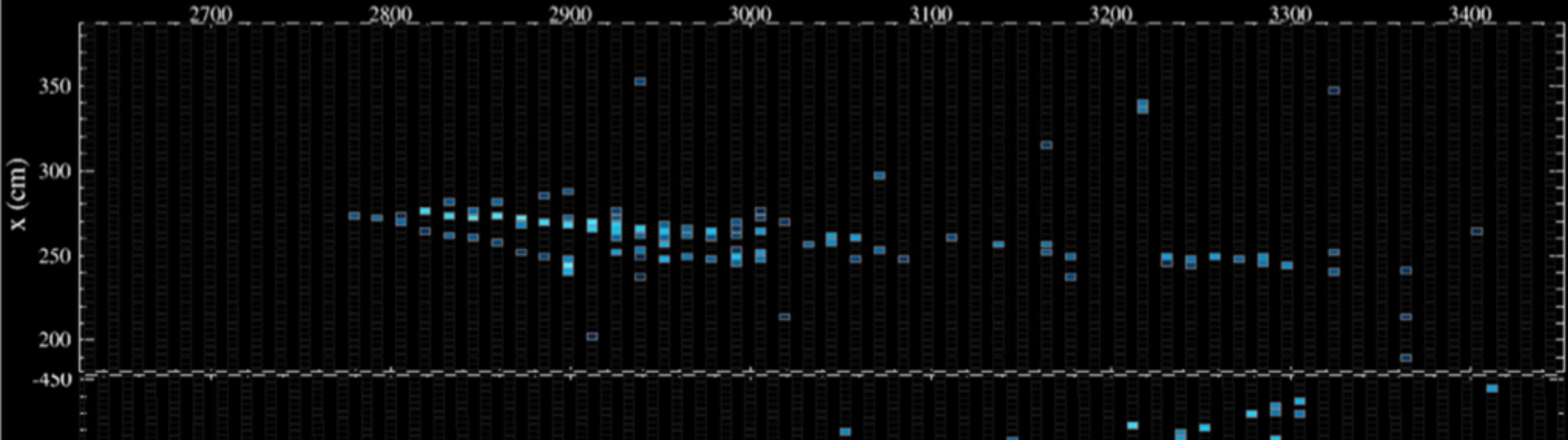


NEXT MUON NEUTRINO DISAPPEARANCE ANALYSIS

- First analyses use conservative systematics
- Need to understand the discrepancy for future analyses:
 - Calibration, detector response, Neutrino interaction modeling, flux modeling.
- External data hints at possible contributions:
 - Missing 2p2h in Genie.
 - MINERvA sees fewer 1pi events than Genie.
 - See W&C seminar tomorrow on 2p2h by Phil Rodrigues for more data.



ELECTRON NEUTRINO APPEARANCE



ELECTRON NEUTRINO APPEARANCE

- The probability of ν_e appearance in a ν_μ beam:

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}}$$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} & \Delta &\equiv \frac{\Delta m_{31}^2 L}{4E} \\ &+ 2\alpha \sin \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta \\ &- 2\alpha \sin \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta \end{aligned}$$

- Searching for ν_e events in NOvA, we can access $\sin^2(2\theta_{13})$.
- Probability depends not only on θ_{13} **but also on δ_{CP}** which might be the key to matter anti-matter asymmetry of the universe.
- Probability is enhanced or suppressed due to **matter effects** which depend on the mass hierarchy i.e. the sign of $\Delta m_{31}^2 \sim \Delta m_{32}^2$ as well as neutrino vs anti-neutrino running.

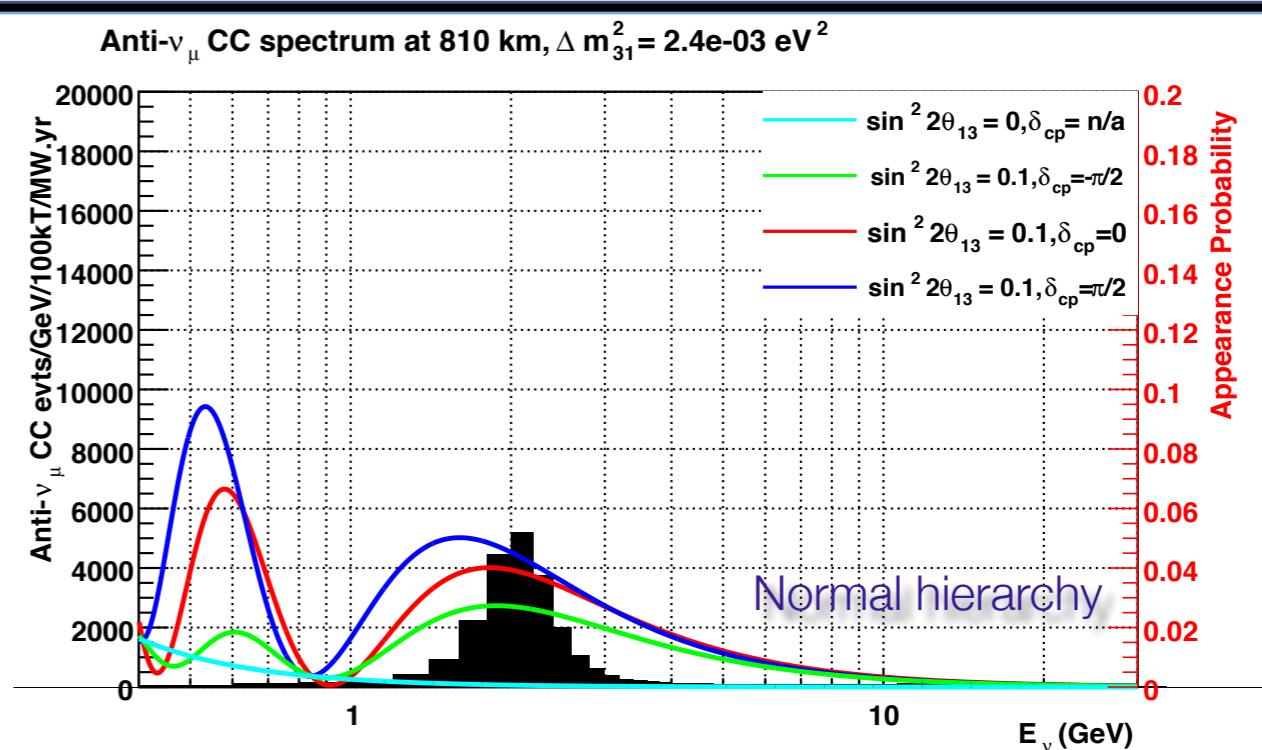
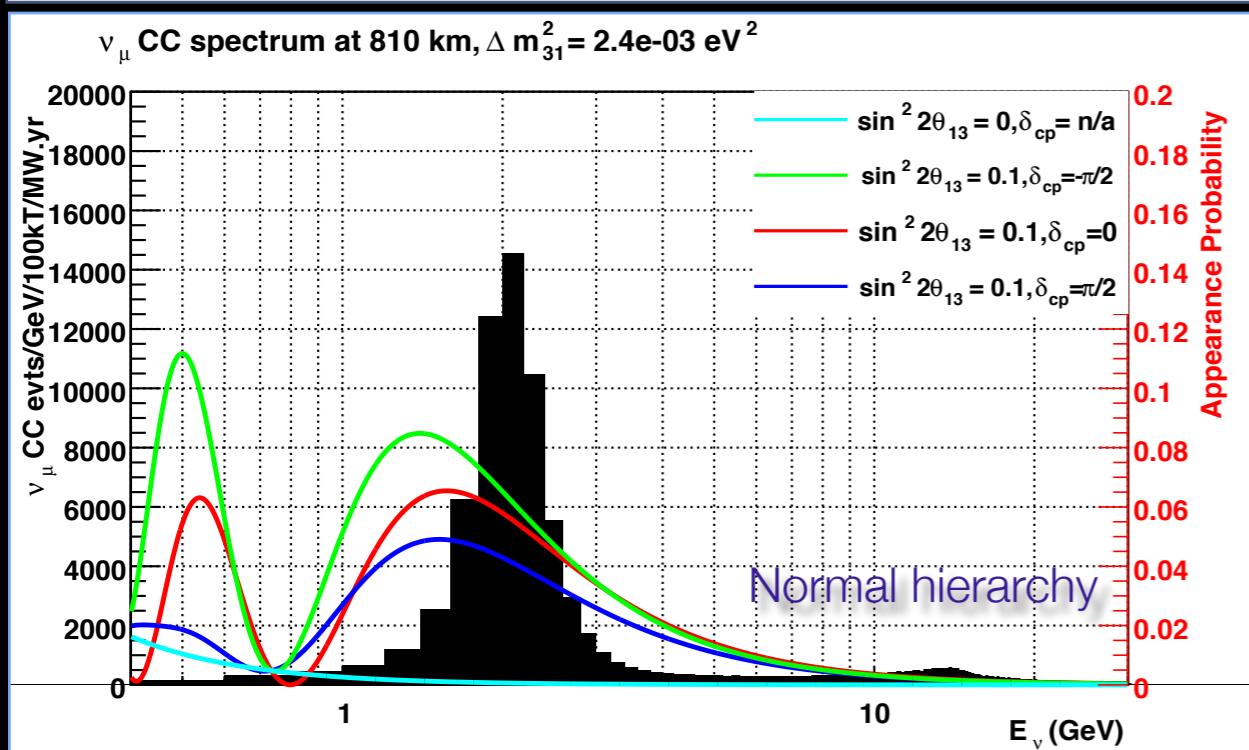
NOVA PROBES THE MASS HIERARCHY AND CP VIOLATION SPACE

ELECTRON NEUTRINO APPEARANCE IN NOVA

- The probability of ν_e appearance in a ν_μ beam:

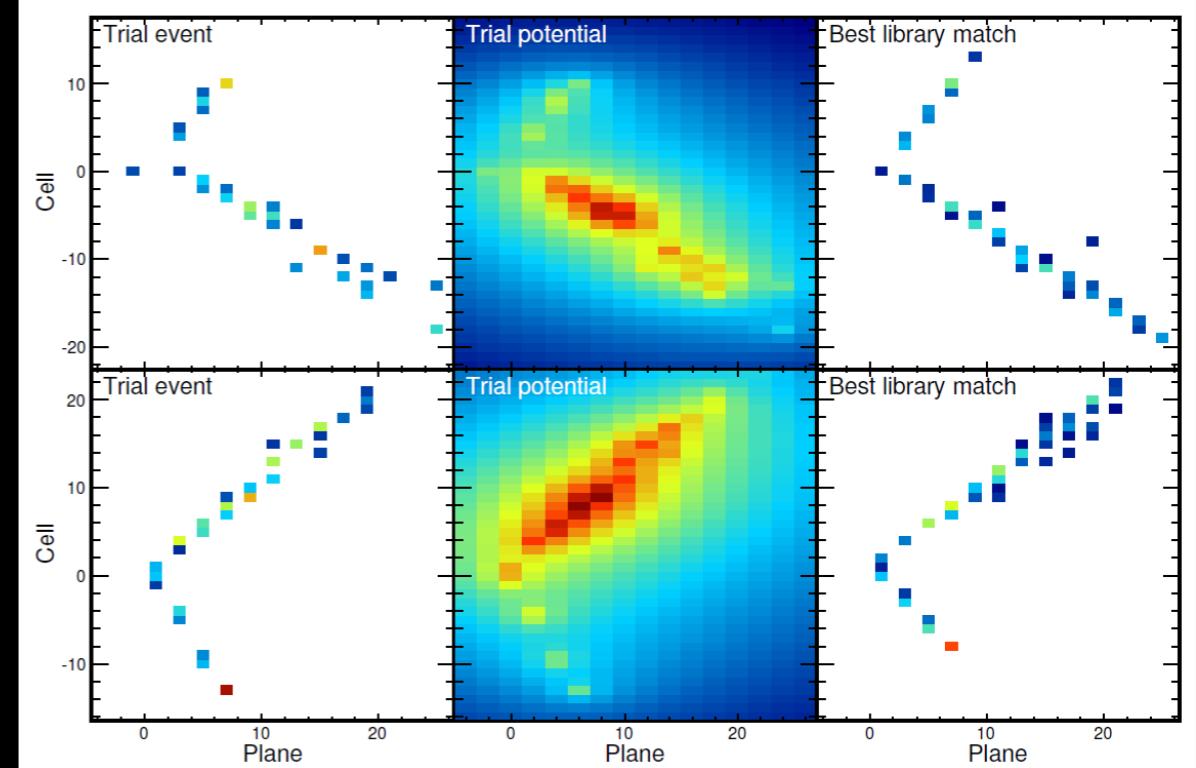
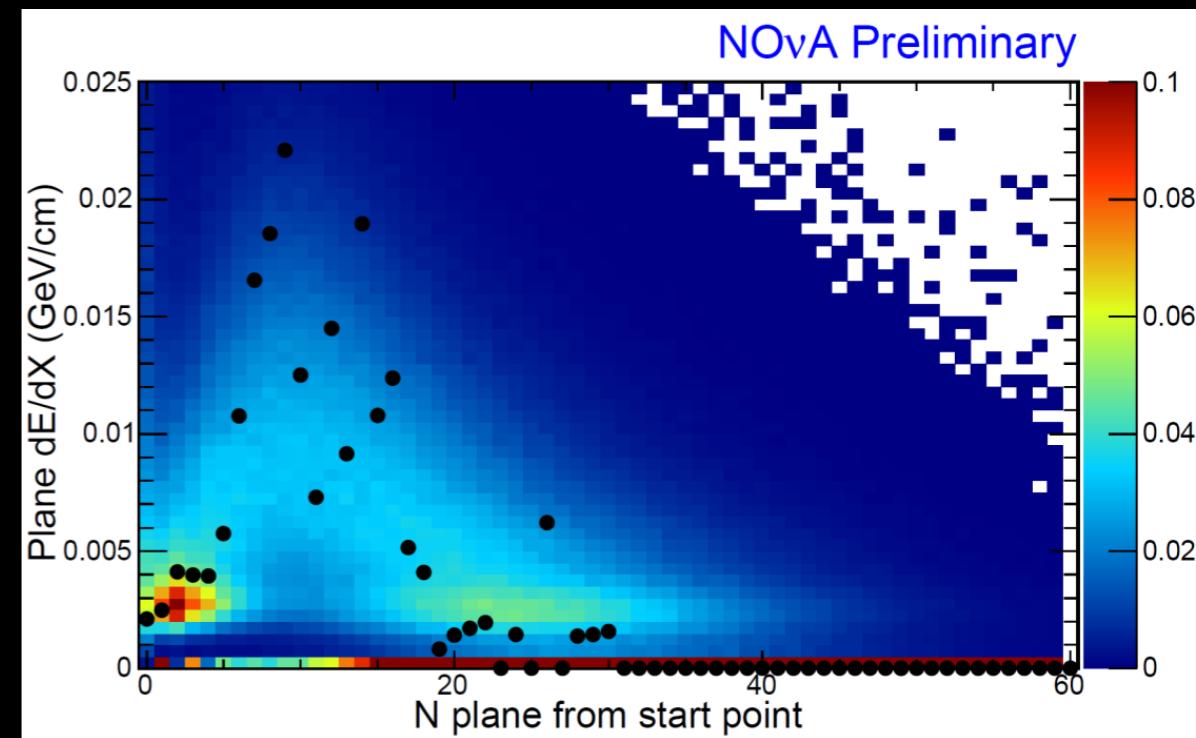
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}}$$

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) &\approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \\
 &+ 2\alpha \sin \theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta \\
 &- 2\alpha \sin \theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta
 \end{aligned}$$



ELECTRON NEUTRINO SELECTION

- Two particle ID algorithms based on pattern recognition techniques have been developed:
 - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for $e/\mu/\pi/p$ particles hypotheses. Uses a neural net.
 - **LEM**: evaluates entire the event topologies against a large Monte Carlo library of signal and background events. Assigns identification to trial event according to top matches in library.
- Good separation of electron neutrino signal from background including cosmic background.

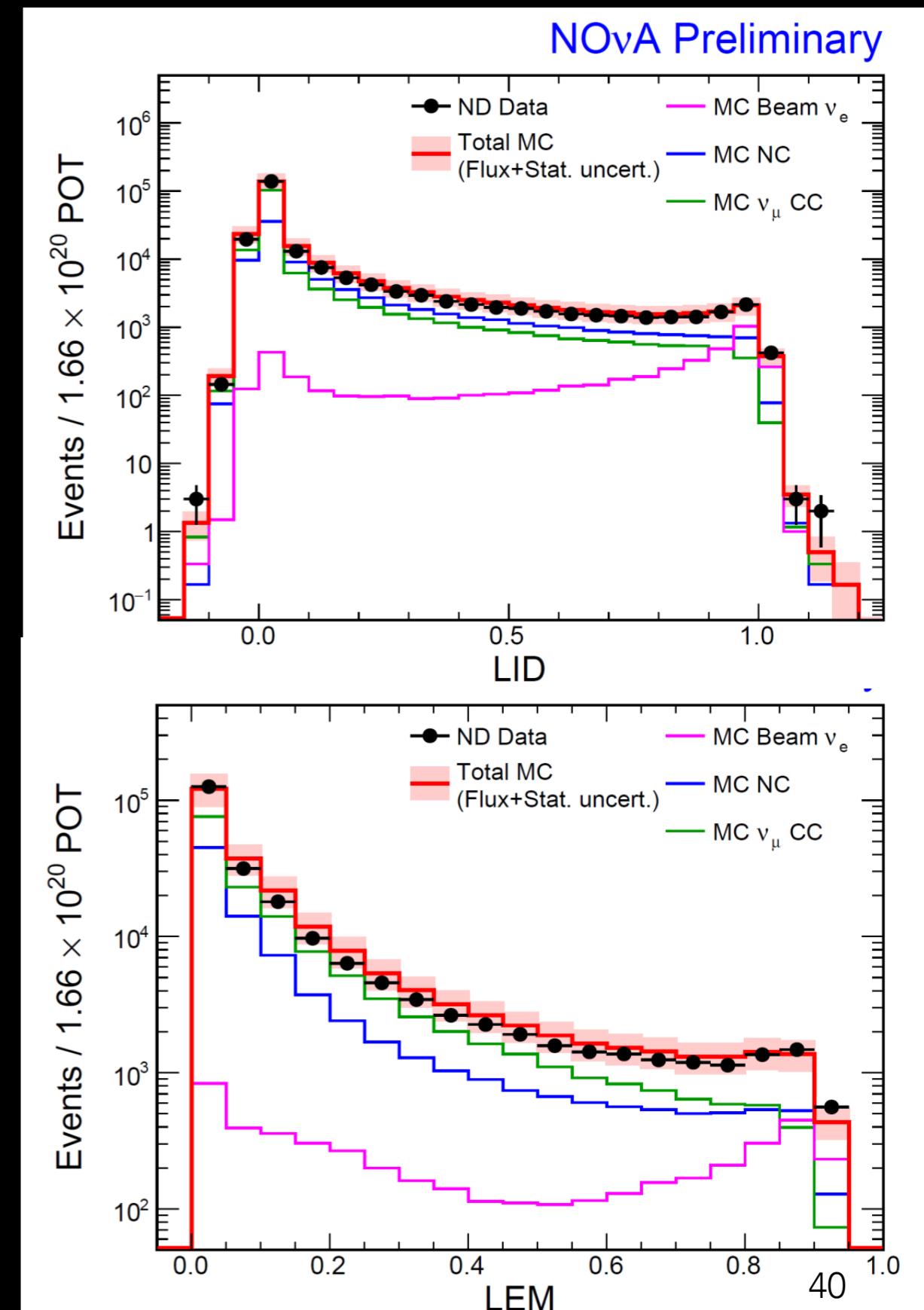


EXPECTED OVERLAP IN LID AND LEM SIGNAL SAMPLES: 62%.

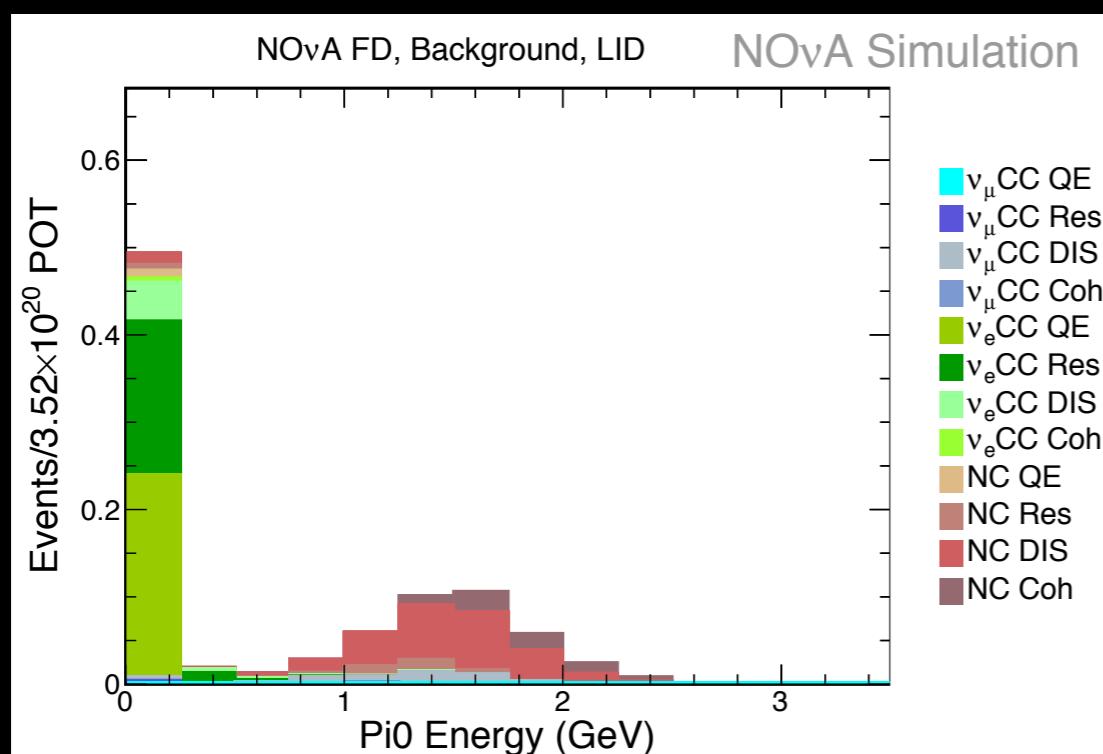
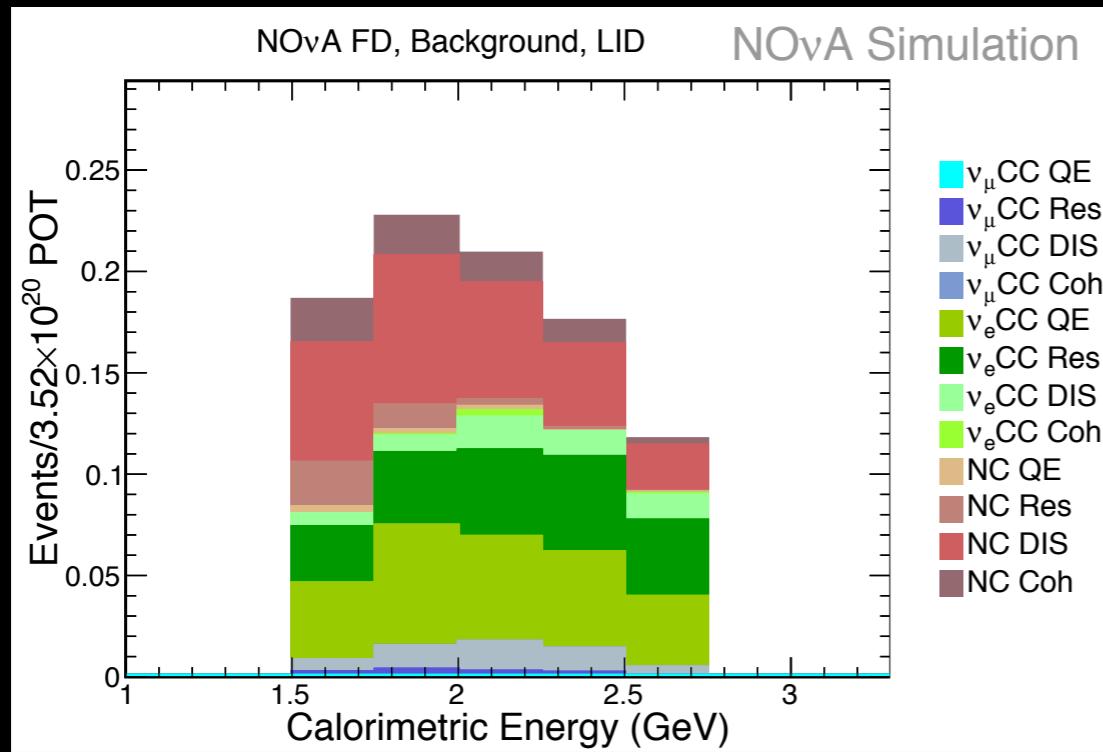
ELECTRON NEUTRINO SELECTION

- Two particle ID algorithms based on pattern recognition techniques have been developed:
 - **LID**: evaluates the leading shower longitudinal and transverse dE/dx profiles against probability density functions for $e/\mu/\pi/p$ particles hypotheses. Uses a neural net.
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PRIOR TO UNBLINDING
DECIDED TO SHOW BOTH
RESULTS AND USE LID AS
PRIMARY SELECTOR



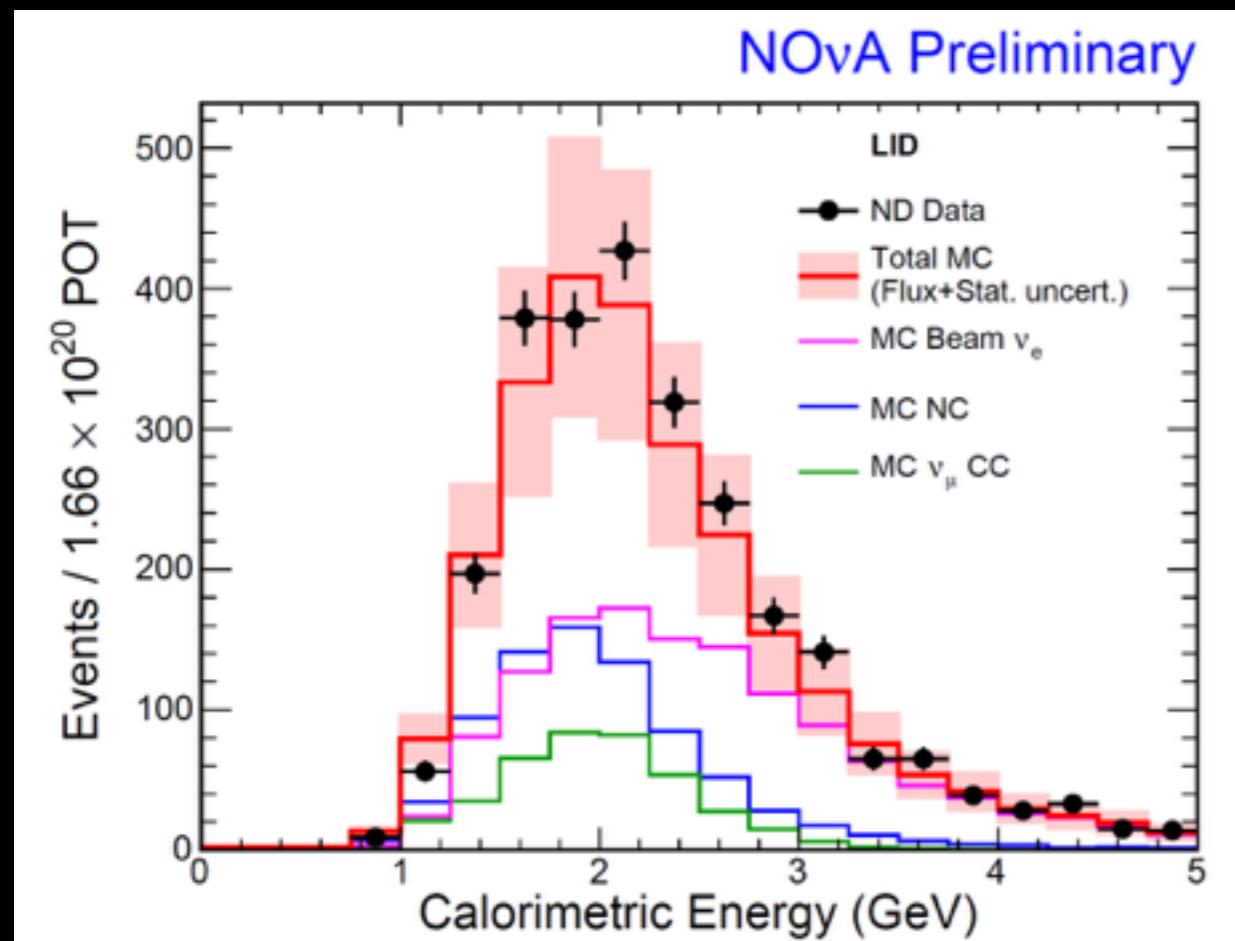
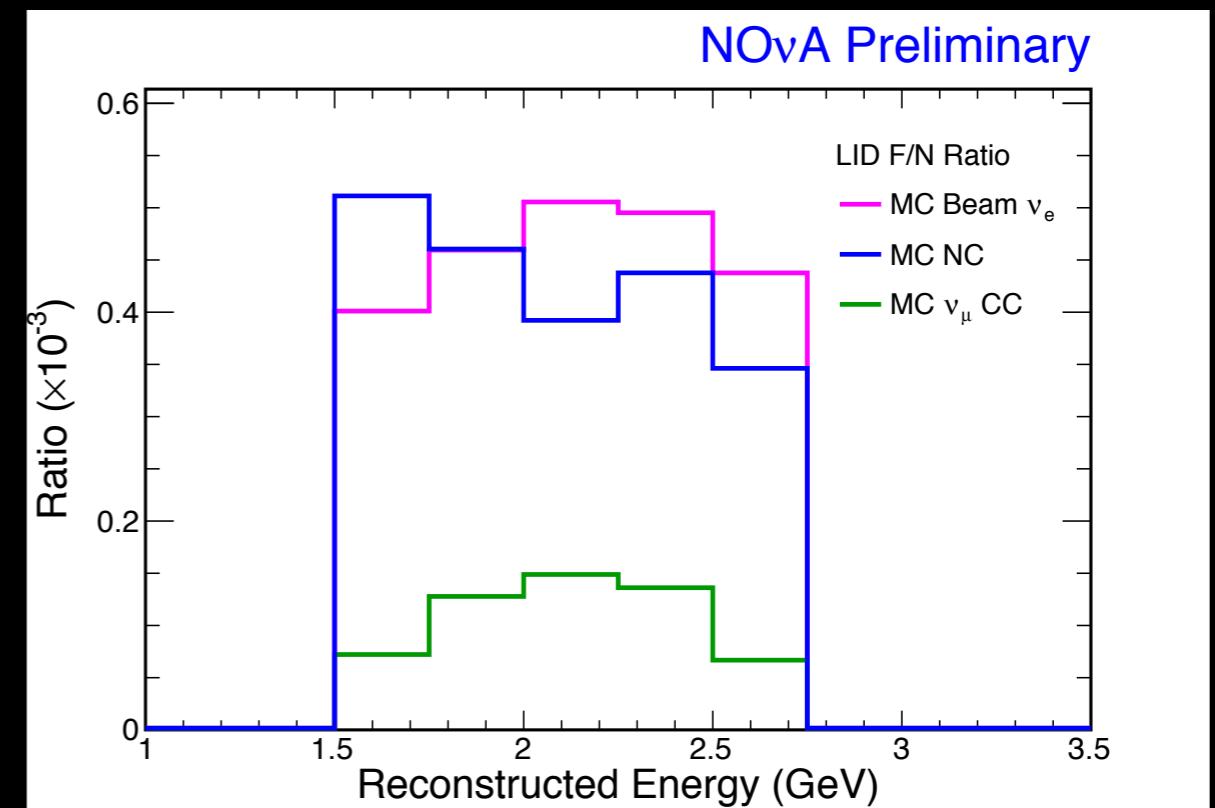
ELECTRON NEUTRINO SELECTION



- Both selection techniques achieve good sensitivity to νe appearance
 - Reject 99.7% of NC backgrounds
 - Better than 1 in 10^8 cosmic rejection
- Selected background in the FD dominated by electron neutrinos from beam contamination and NC DIS.
 - Most of the latter have a π^0 with energy similar to expected signal.

PREDICTING THE BACKGROUND IN THE FD

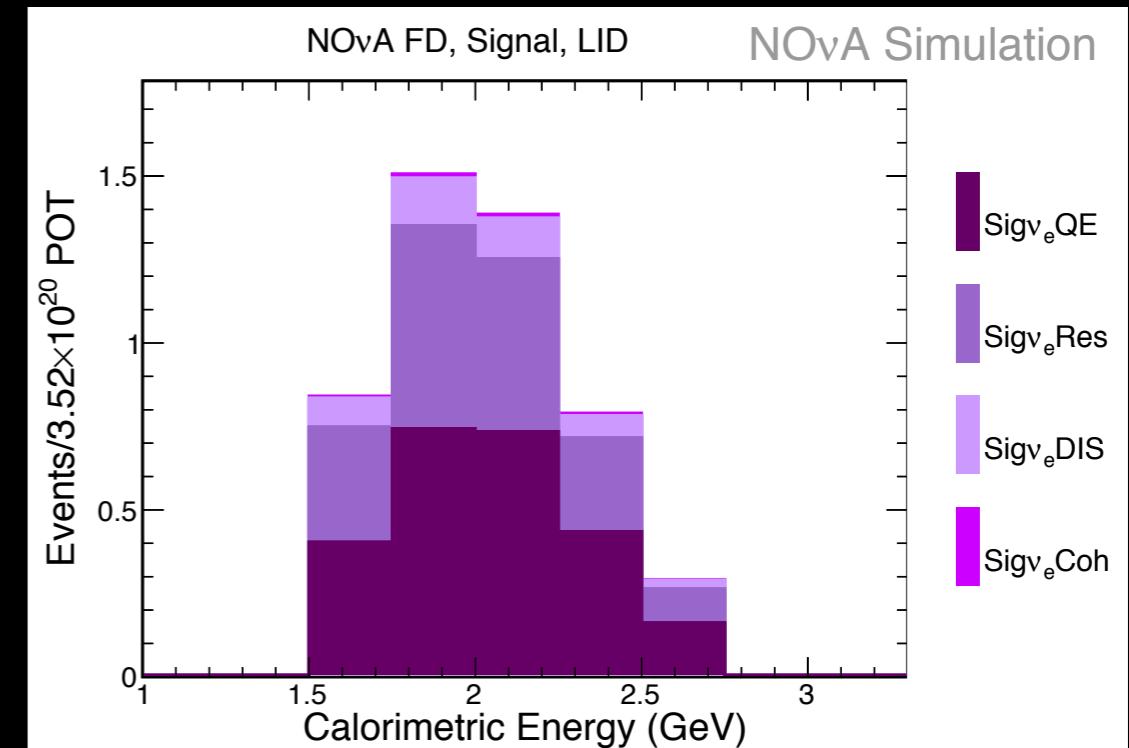
- Calorimetric energy after electron neutrino selection (shown for LID) shows good agreement.



- ND data is translated to FD background expectation in each energy bin, using Far/Near ratios from simulation.
- A small 5% excess in data is observed in the ND which is used as a correction to the FD background prediction.

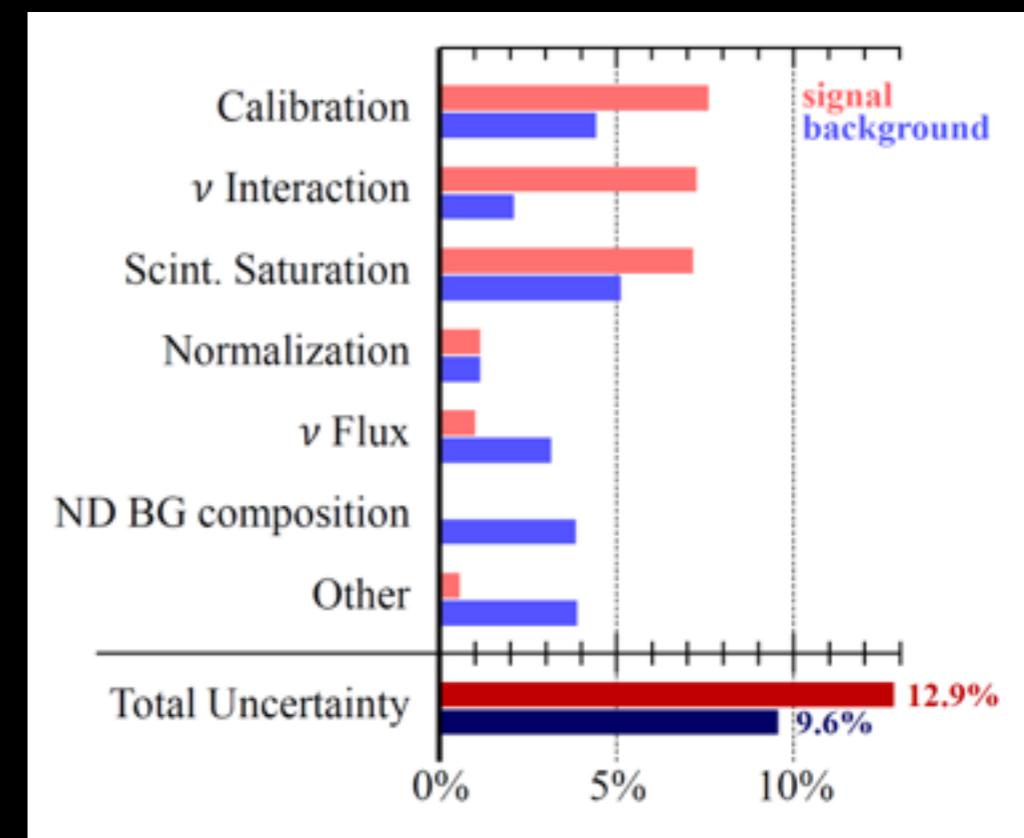
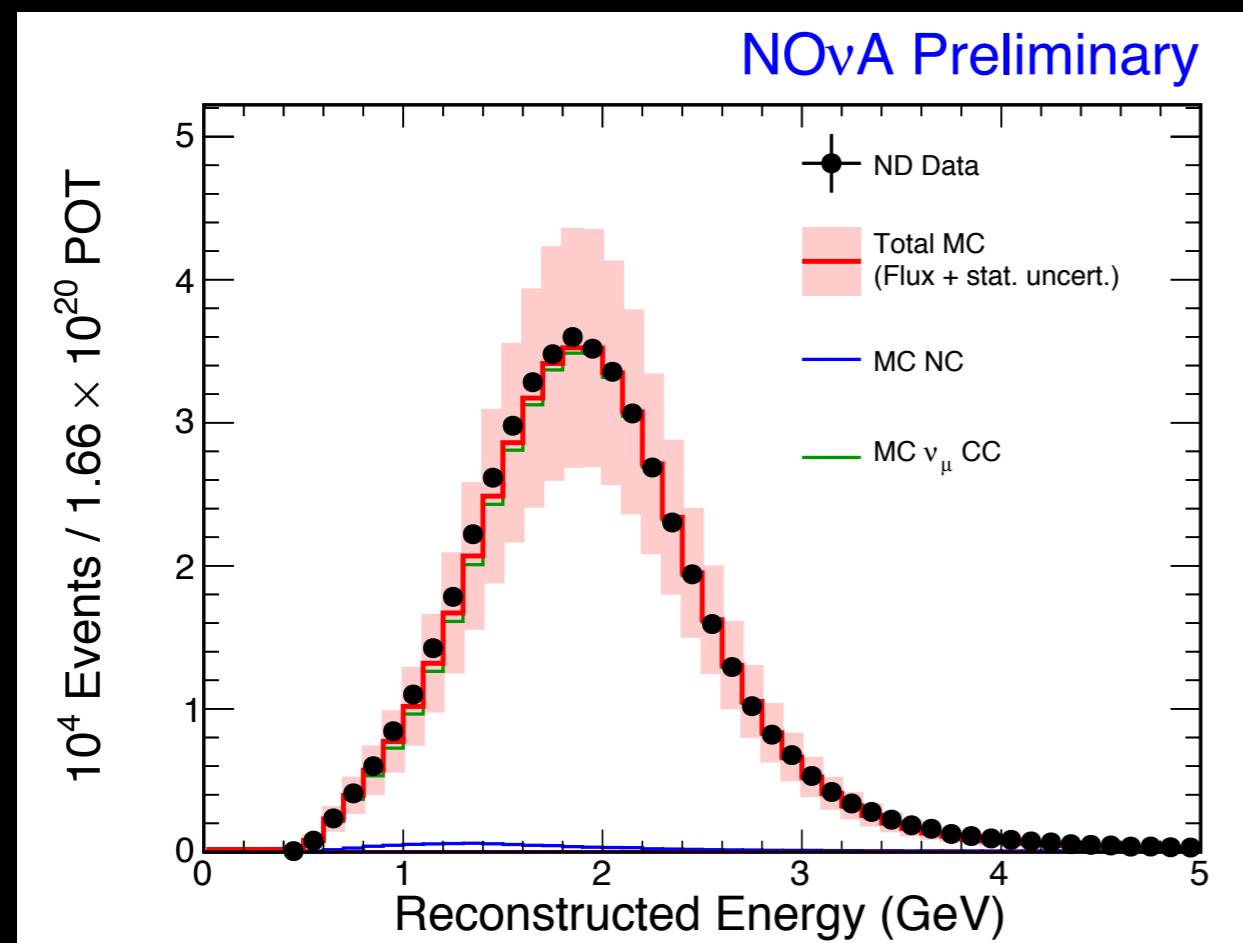
ELECTRON NEUTRINO SELECTION

- Both selection techniques achieve good sensitivity to electron neutrino appearance:
 - 35% signal selection efficiency with respect to contained events.
- Signal dominated by quasi-elastic and resonance interactions. Expect minimal impact from hadronic system.
- Selection efficiency varies by process type:
 - QE selection efficiency is 2x RES selection efficiency, which is 2x DIS selection efficiency
 - Uncertainties in relative components implies uncertainty in signal selection efficiency.



PREDICTING THE SIGNAL IN THE FD

- FD signal expectation is predicted using the ND-selected ν_μ CC spectrum using same technique as for muon neutrino disappearance.

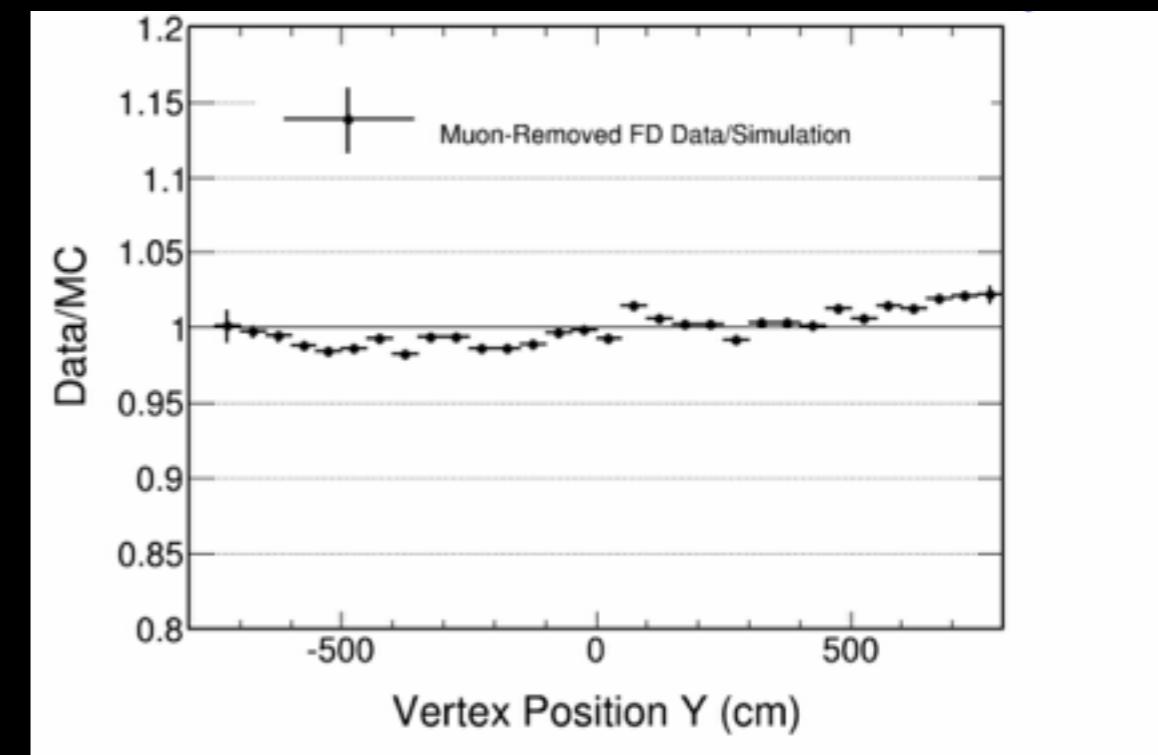
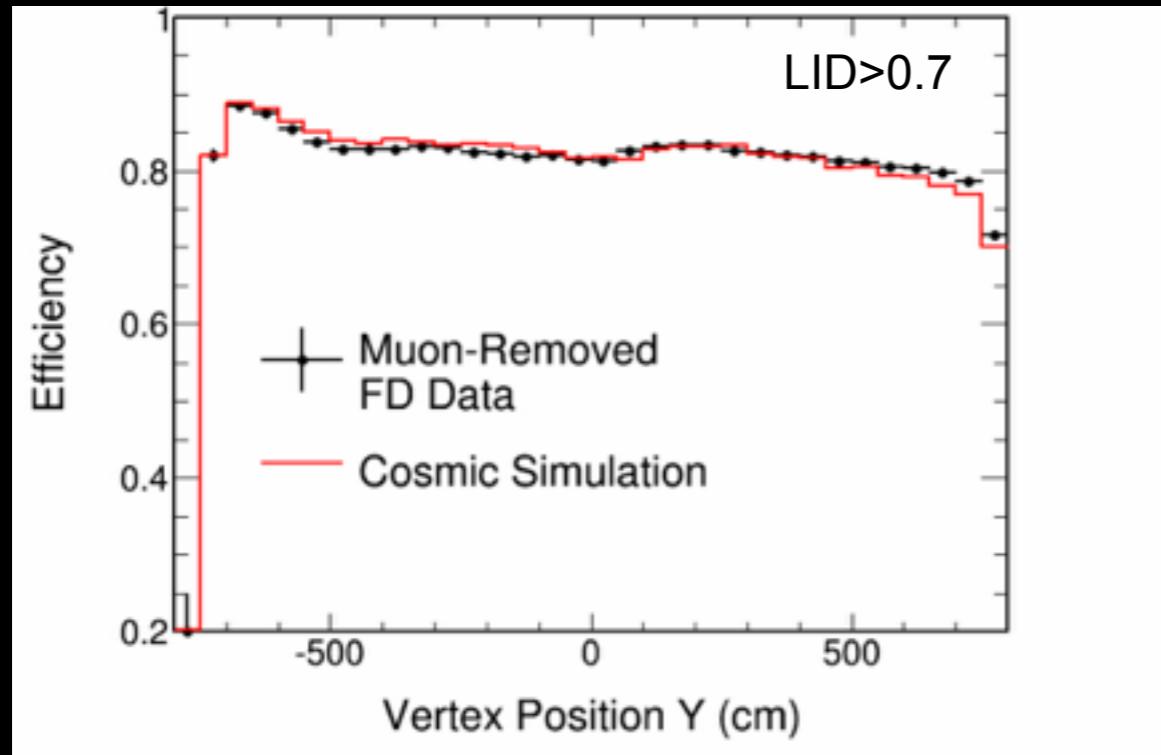
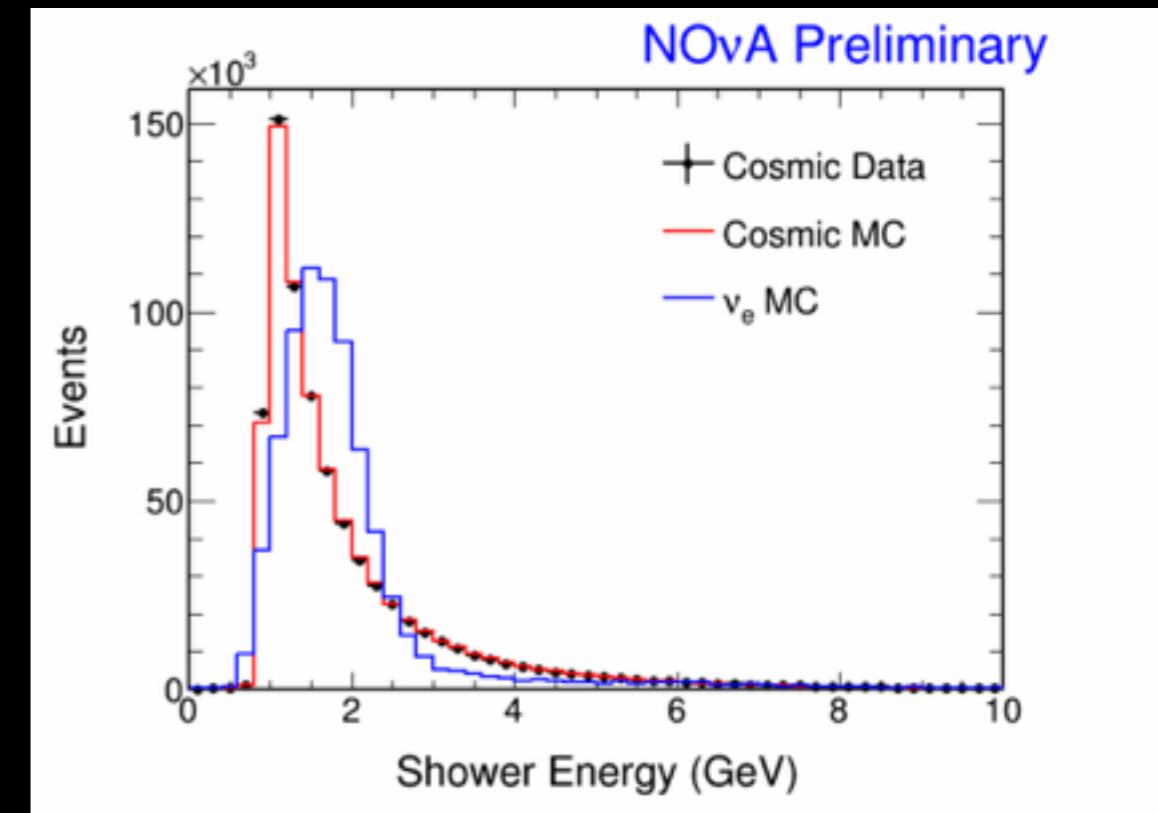


- Most systematics are assessed by modifying the Far/Near simulated ratios and calculating the variation in the prediction both for signal and background.
- Signal selection efficiency not benchmarked in ND.

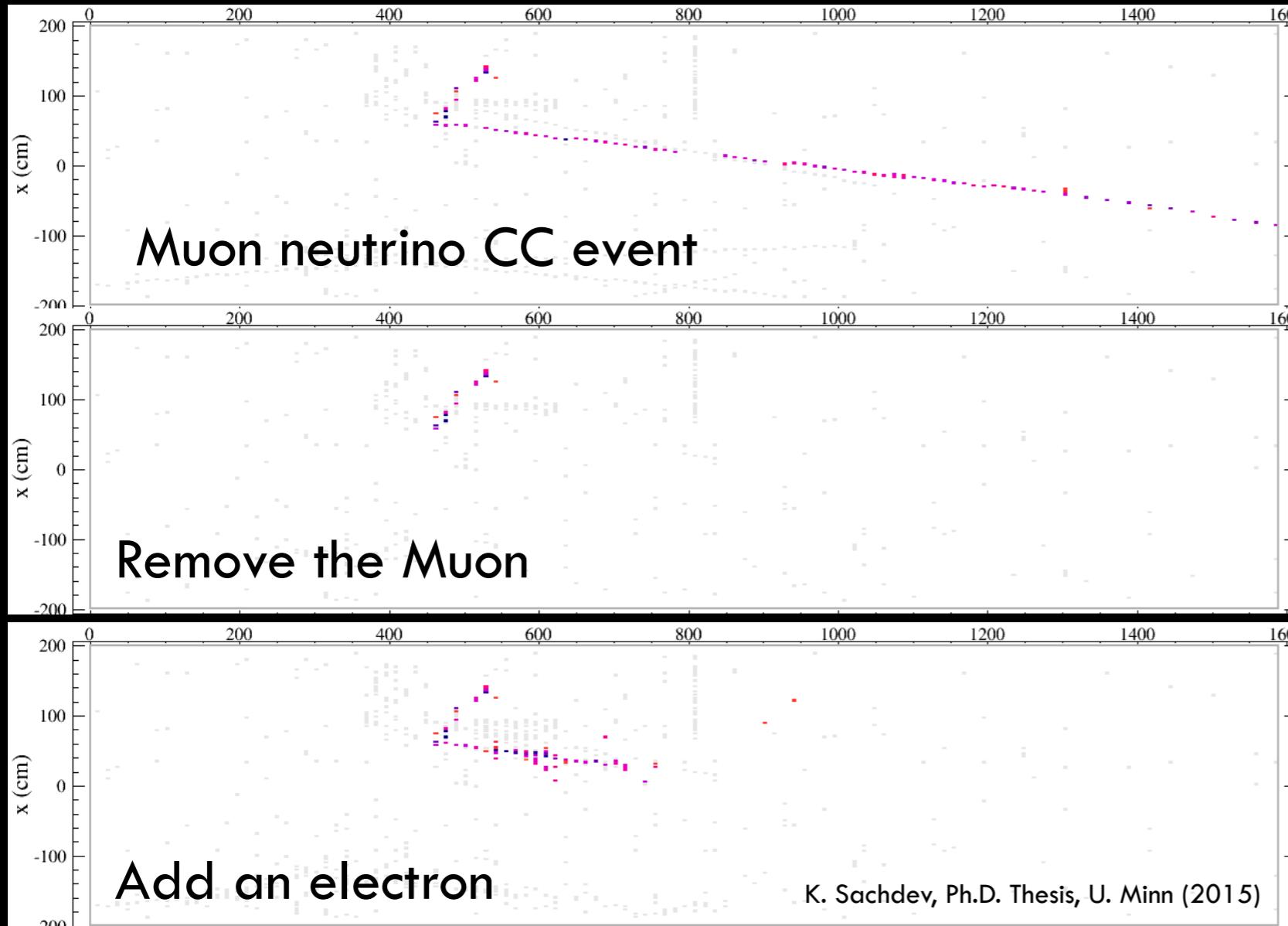
SEVERAL INDEPENDENT EM SAMPLES SHOW GOOD DATA/MC AGREEMENT

STUDYING EM SHOWER MODELING

- We use bremsstrahlung photons to demonstrate good EM shower modeling in the FD in the relevant energy range.
- Variation in selection efficiency across the face of the detector is well model (within few percent).



MAKING ELECTRON NEUTRINOS



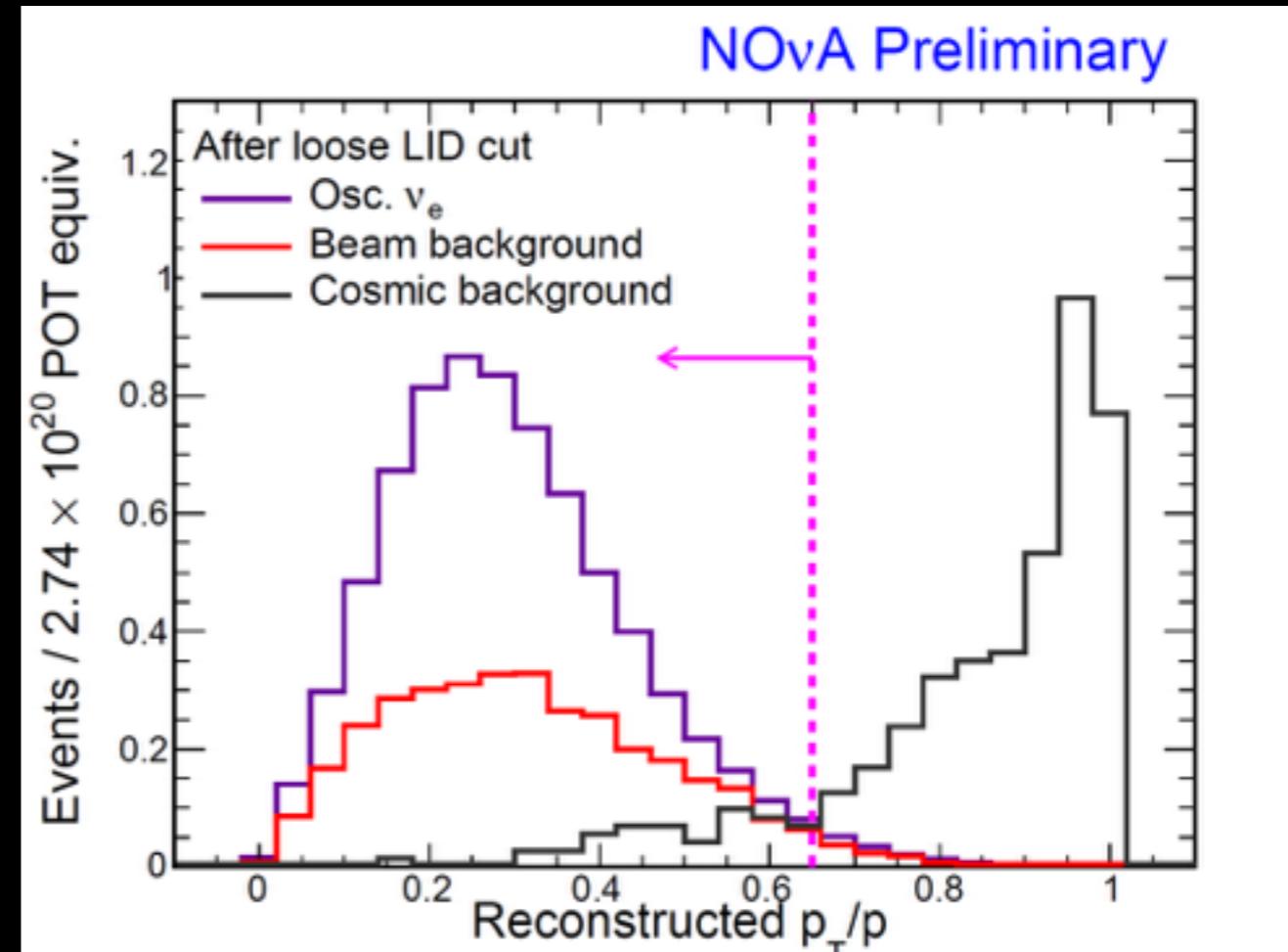
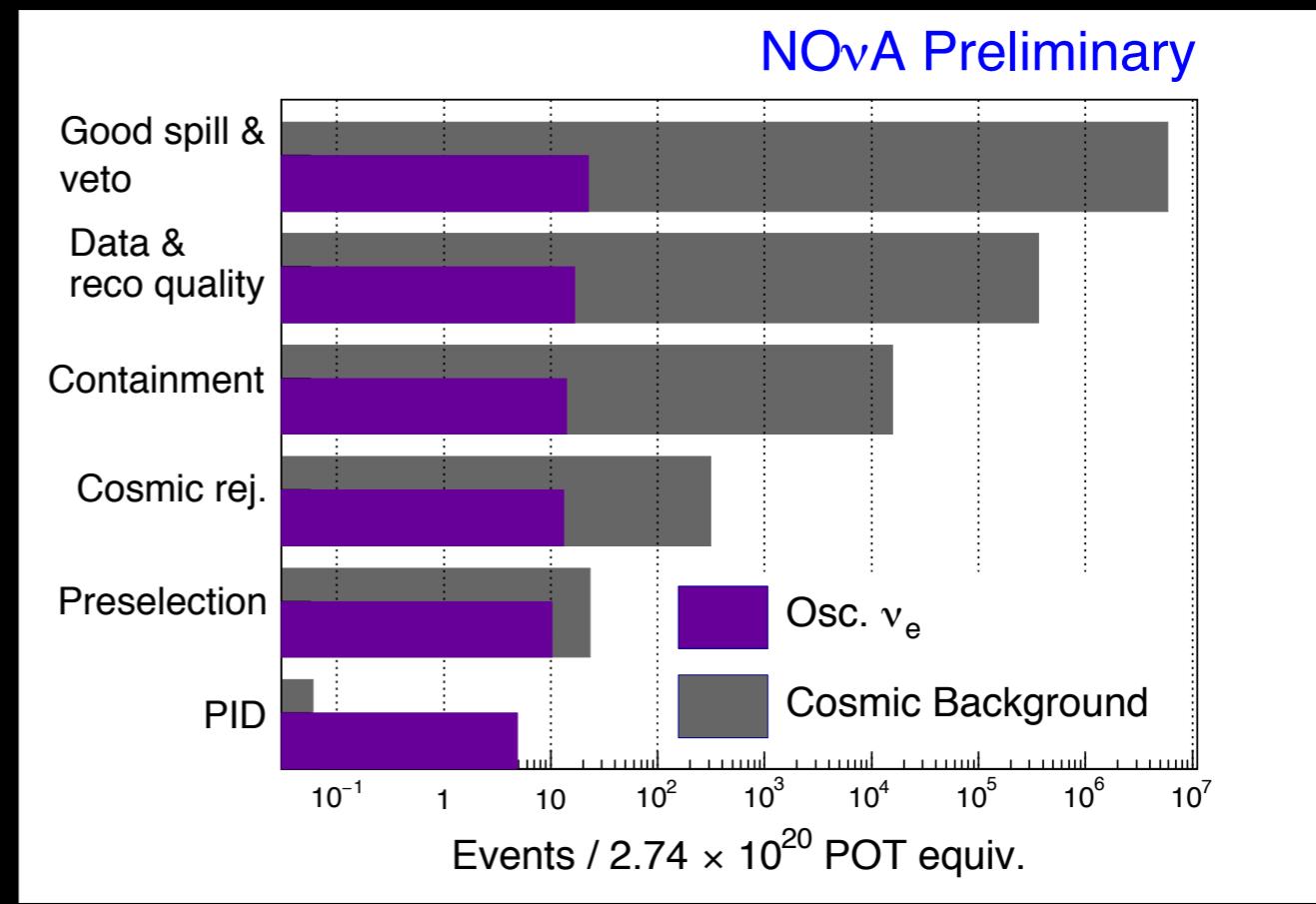
- In order to study signal efficiency in ND events we can use data/simulation hybrid events:
- Remove the hits associated with a muon track in selected numu CC event
- Insert a simulated electron with the same kinematics as the removed muon
- Reconstruct the hybrid event .

- Comparing distributions between data and MC will help constrain the selection efficiency of electron neutrino events.
- This could provide a model independent systematic uncertainty estimate for the signal.

COSMIC REJECTION FOR ELECTRON NEUTRINOS

- Containment and topological cuts such as removing events with large p_T/p remove significant factors of this background.
- The electron neutrino selectors themselves provide the remaining level of rejection to achieve 10^8 removal of cosmic ray interactions.
- Measurement of background on out-of-time spill data.

EXPECTED COSMIC
BACKGROUND: 0.06 EVENTS



THE PREDICTION

- Background predictions are about 1 count each, 10% error. Few percent dependence on other oscillation parameters.
- Dominated by beam electron neutrinos and neutral current interactions.
- Cosmic background comparable to smallest beam backgrounds.

PID	total bkg	ν_e CC bkg	NC bkg	ν_μ CC bkg	ν_μ CC bkg	cosmic bkg
LID	0.94 ± 0.09	0.46	0.35	0.05	0.02	0.06
LEM	1.00 ± 0.11	0.46	0.40	0.06	0.02	0.06

- Signal prediction depends on oscillation parameters, the extremes are:

$$2 \pm 0.3 \text{ (IH } \delta_{CP} = \pi/2) \longleftrightarrow 6 \pm 0.7 \text{ (NH } \delta_{CP} = 3\pi/2)$$

THE ANSWER

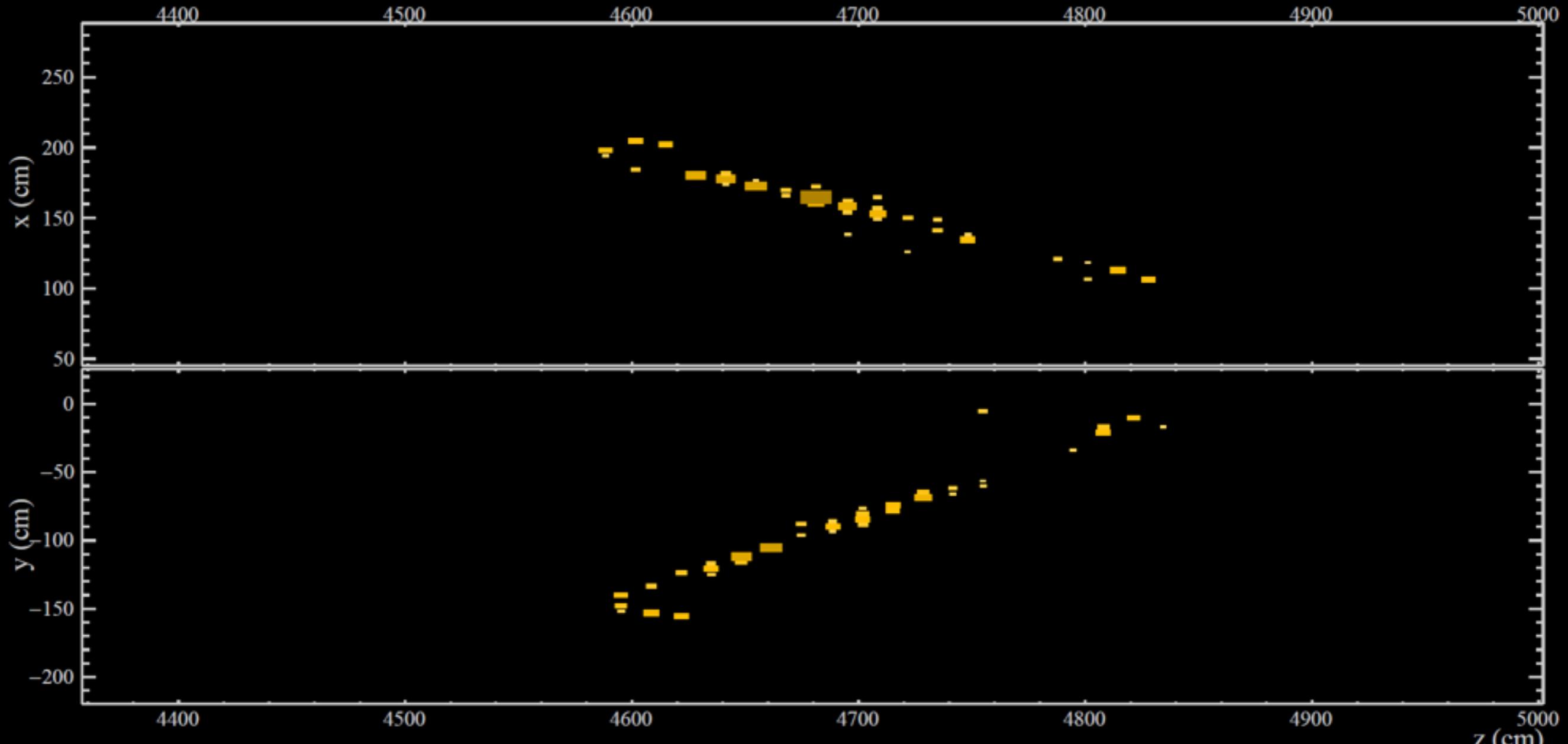
- Background predictions for both selectors are about 1 count each, 10% systematic. Few percent dependence on oscillation parameters.
- Dominated by beam electron neutrinos and NC.
- Cosmic background comparable to smallest beam backgrounds.

PID	total bkg	ν_e CC bkg	NC bkg	ν_μ CC bkg	ν_μ CC bkg	cosmic bkg
LID	0.94±0.09	0.46	0.35	0.05	0.02	0.06
LEM	1.00±0.11	0.46	0.40	0.06	0.02	0.06

- We observe:

6 ELECTRON
NEUTRINOS
(11 WITH LEM)

ELECTRON NEUTRINO CANDIDATE



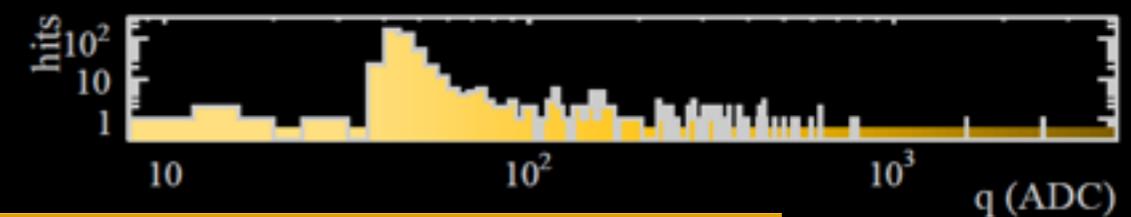
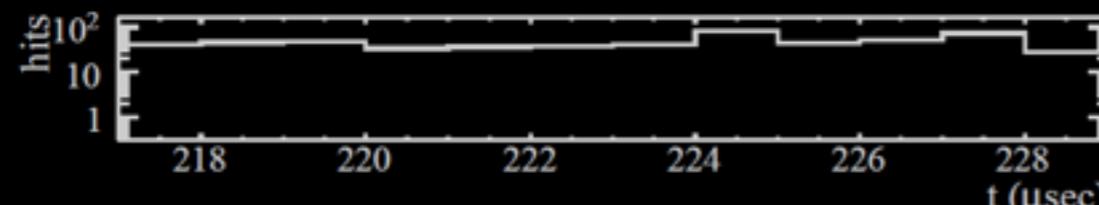
NOvA - FNAL E929

Run: 19165 / 62

Event: 920415 / -

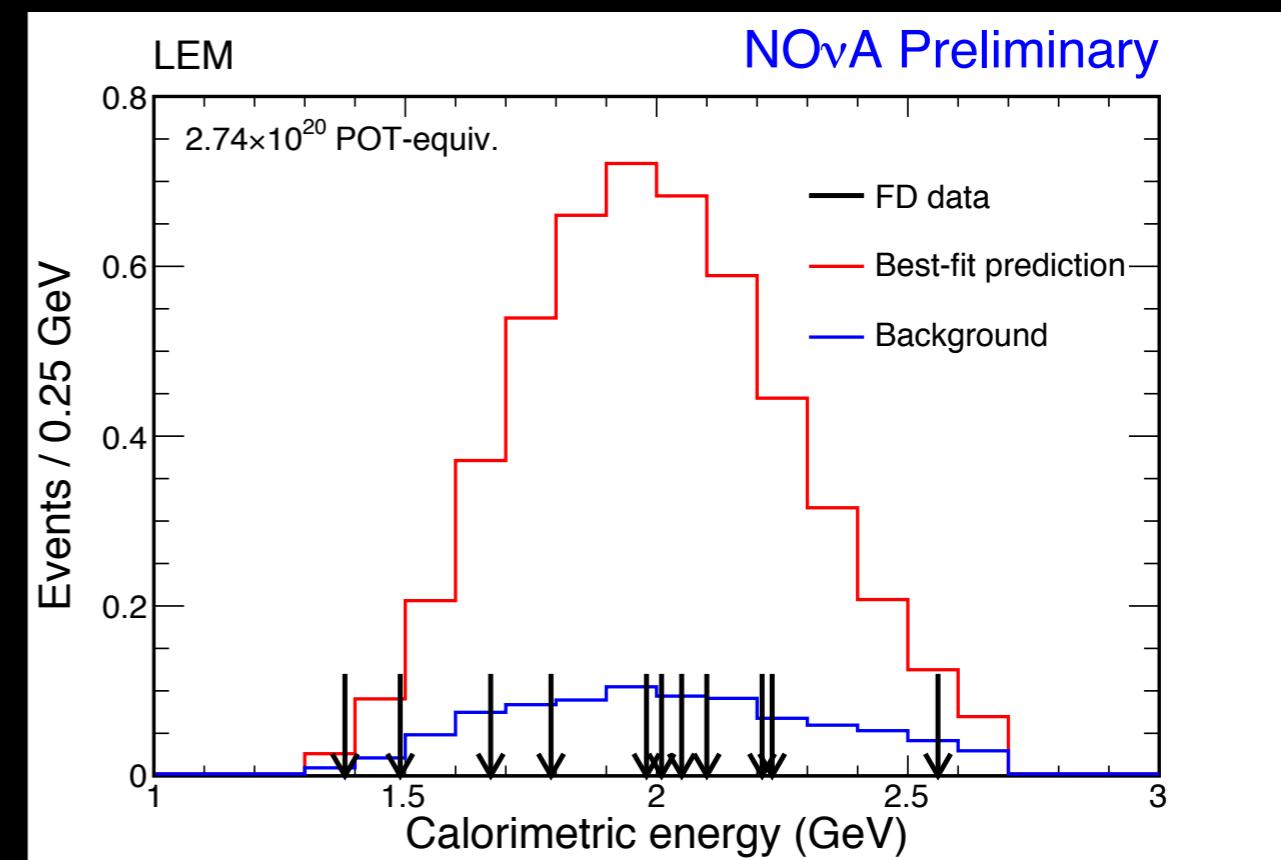
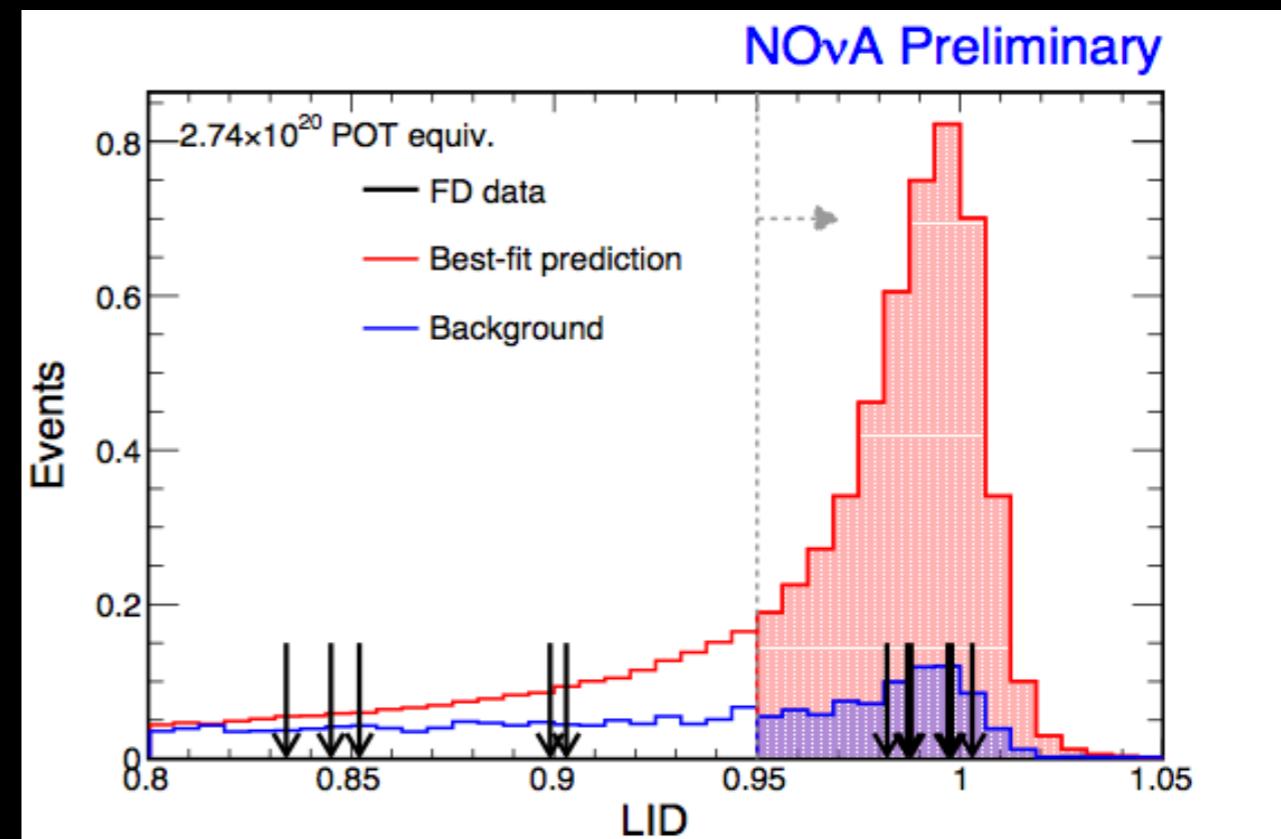
UTC Mon Mar 23, 2015

11:43:54.311669120



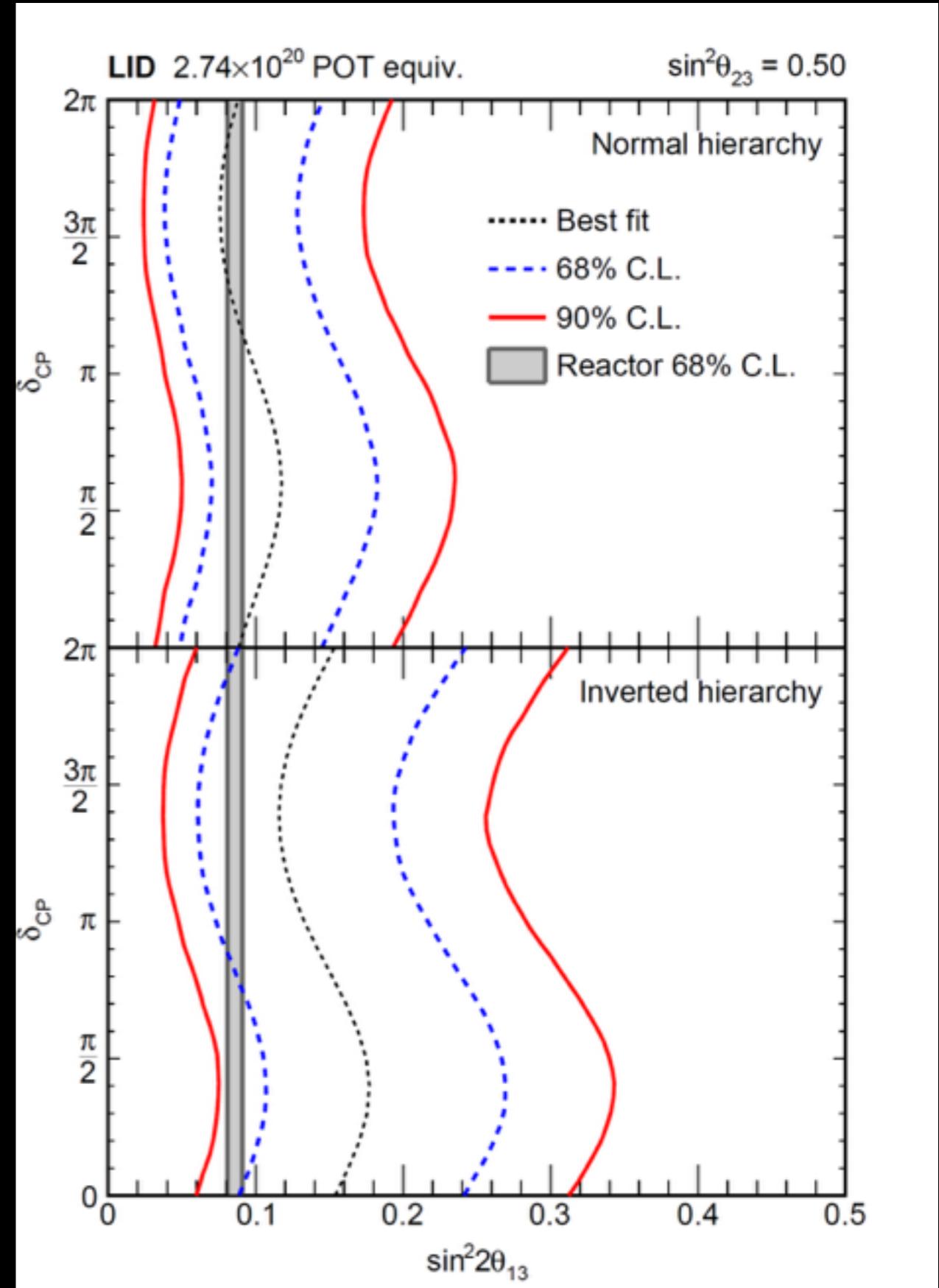
ELECTRON NEUTRINO SELECTED EVENTS

- LID selects 6 events. The significance of appearance is 3.3σ
- LEM selects 11. The significance of appearance is 5.5σ
- The expected background in each case is 1 event.
- All 6 of LID events are also selected by LEM. The P-value for selecting the combination (11:6/5/0) is 9.2%.
 - Note that LID and LEM have a difference in energy cuts in the low end.
 - Other reassuring distributions include time, spatial and angular distributions.



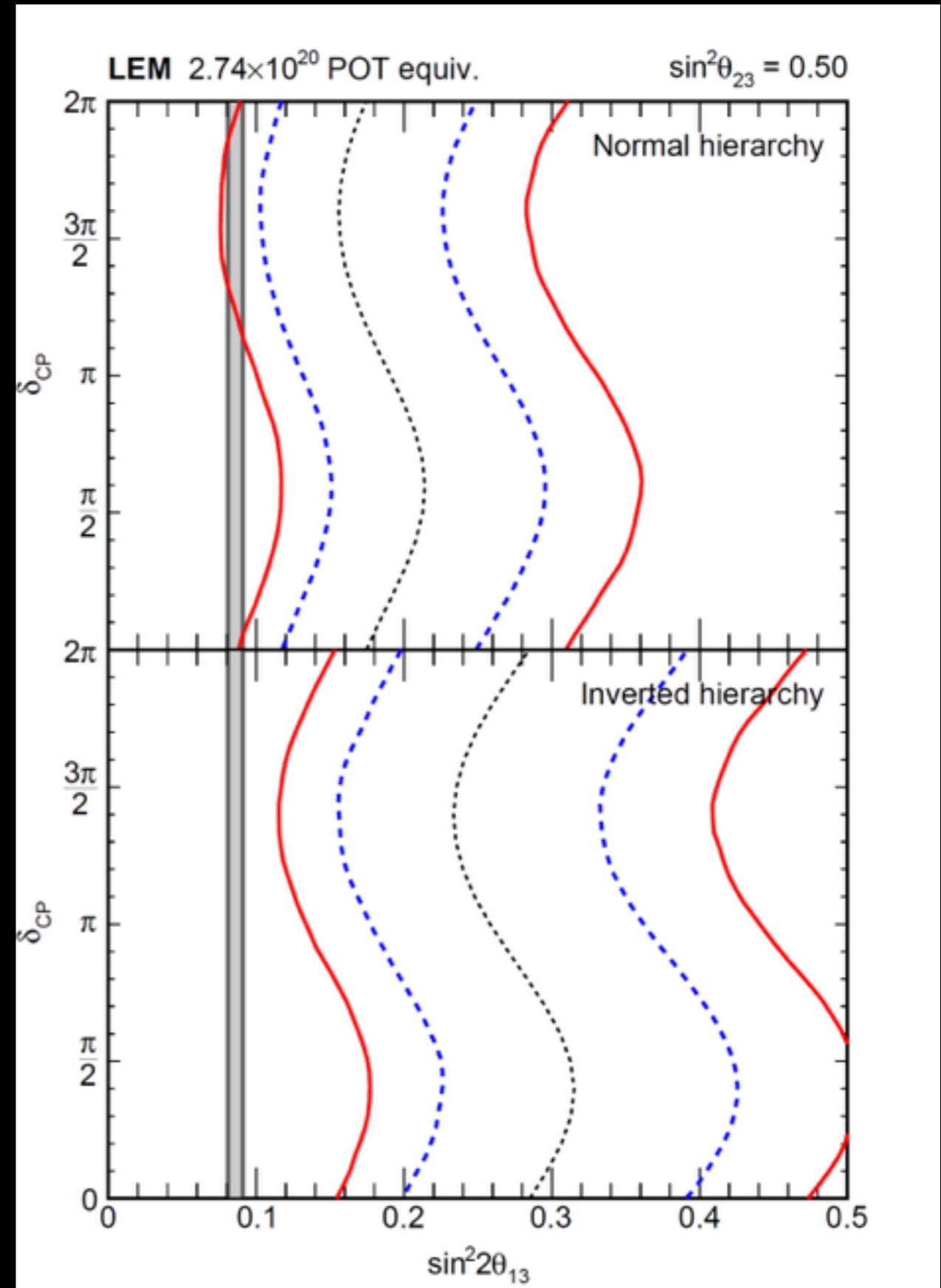
ELECTRON NEUTRINO APPEARANCE RESULTS

- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is $\sim 1\sigma$ better for the normal ordering.
- This plot is for LID selector ($n=6$).



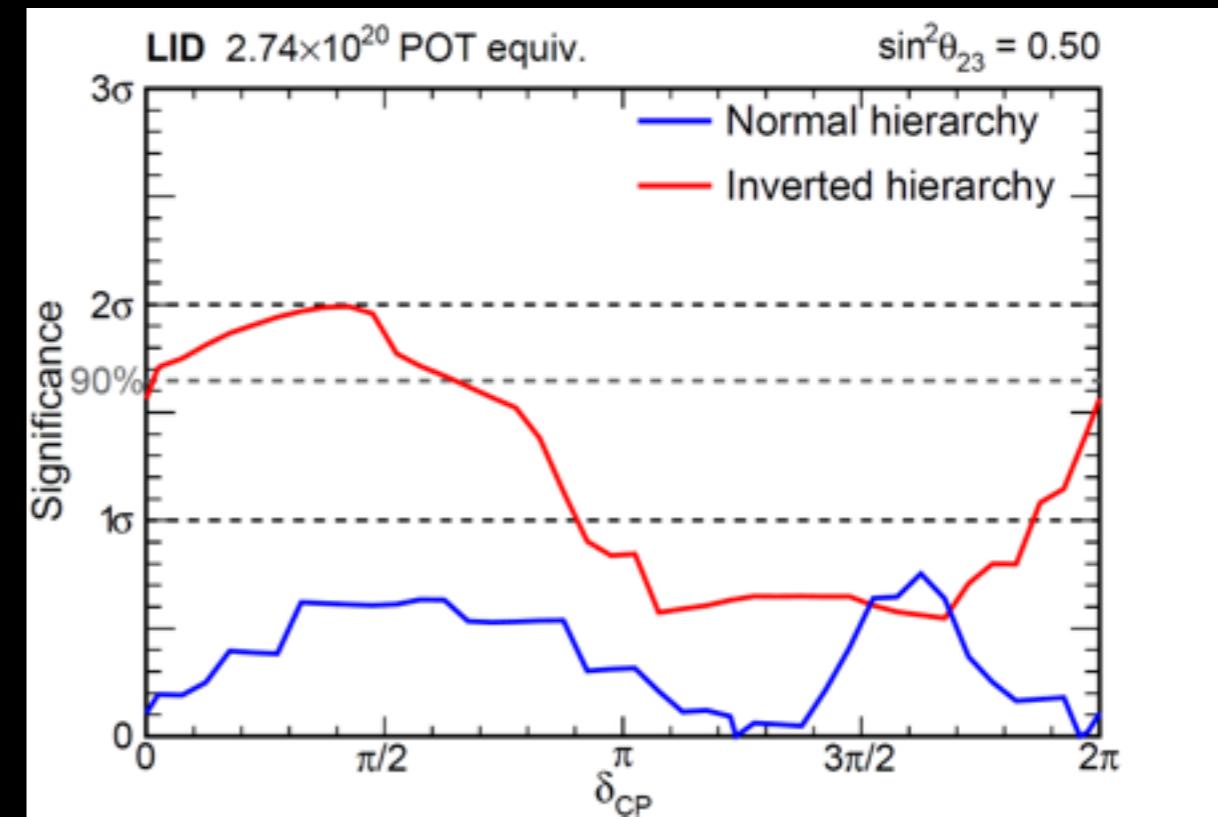
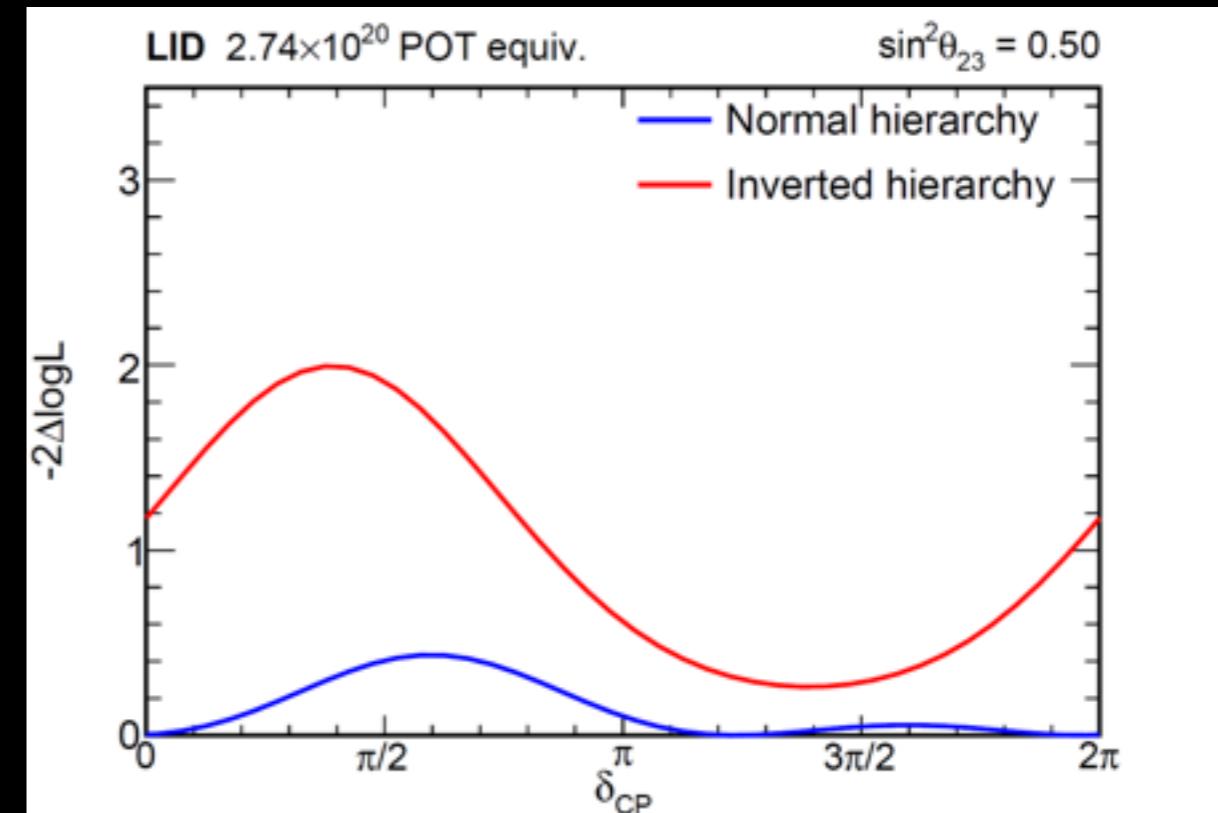
ELECTRON NEUTRINO APPEARANCE RESULTS

- Results show good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is $\sim 1\sigma$ better for the normal ordering.
- For LEM ($n=11$) the s-curves shift by a factor of 2 to the right increasing tension for the inverted mass ordering.



ELECTRON NEUTRINO APPEARANCE RESULTS

- Taking the reactor measurement of θ_{13} as an input, we can explore compatibility with the mass hierarchy and δ_{CP} using Feldman-Cousins.
- There is a significant deviation from gaussian limits in this case. Also non-smooth shape due to discreet nature of counting experiment.
- Resulting significances show that at maximal mixing, we disfavor the IH for $\delta \in [0, 0.6\pi]$ at 90% C.L. with primary selector.



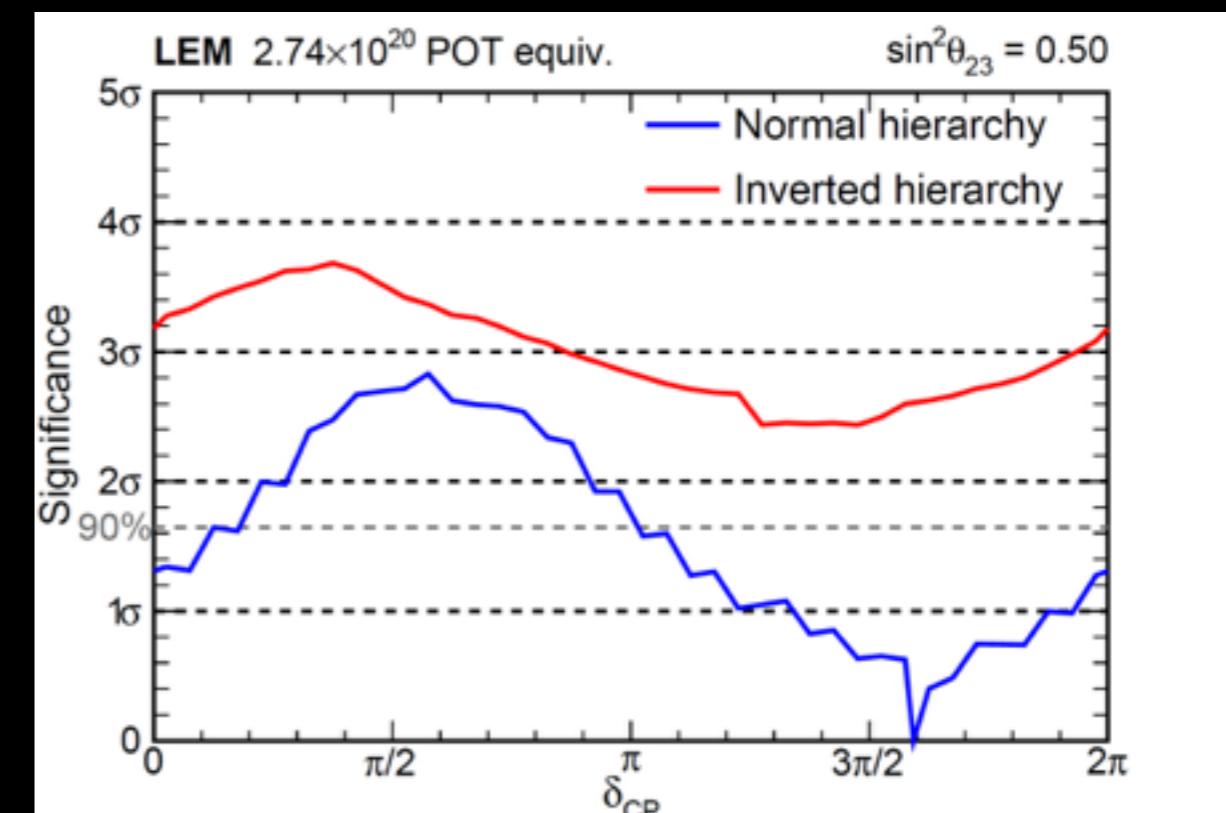
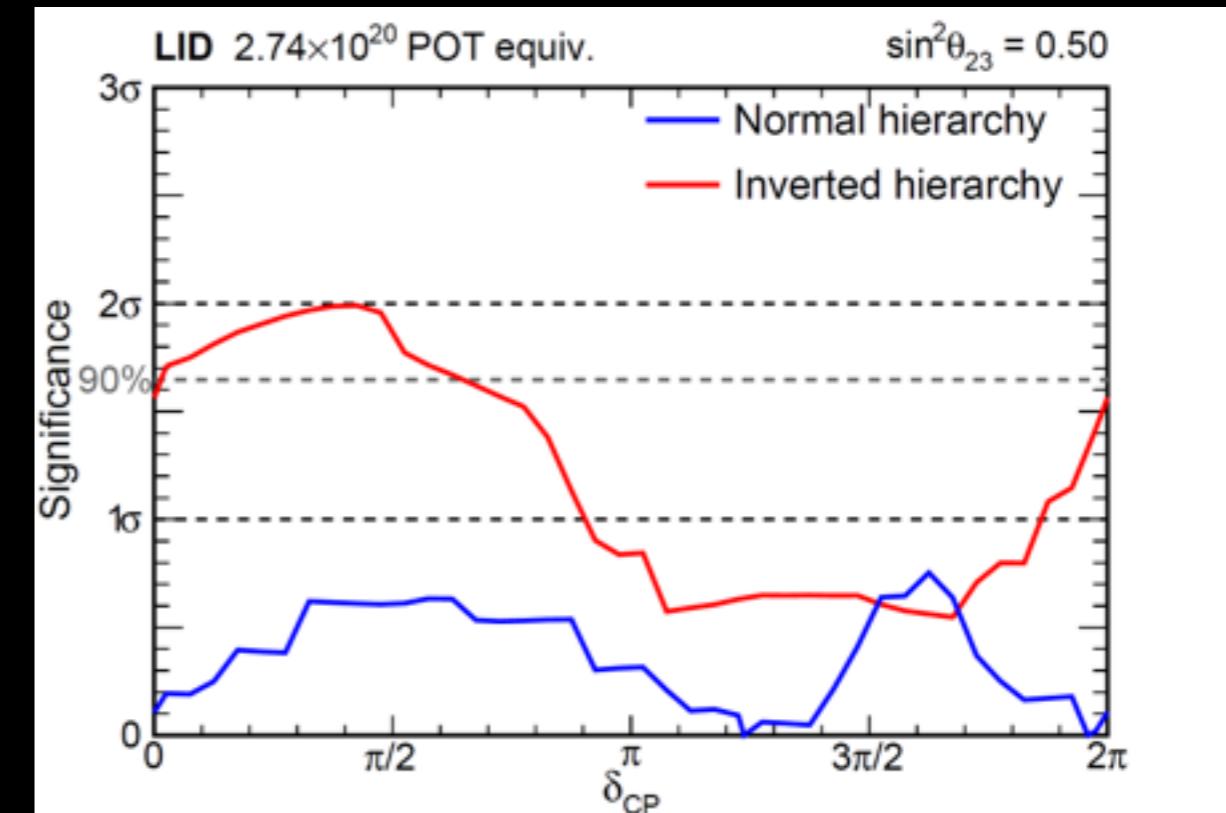
with $\sin^2 2\theta_{13} = 0.086 \pm 0.005$

ELECTRON NEUTRINO APPEARANCE RESULTS

- Both selectors prefer normal hierarchy.
- Both selectors prefer δ near $3\pi/2$.
- Given expected correlations, the observed event counts yield a reasonable mutual p-value of 9.2%.
- The specific point IH, $\delta=\pi/2$ is disfavored at 1.6σ (LID) and 3.2σ (LEM)* for $\sin^2\theta_{23} = 0.4-0.6$.

CONSISTENT HINTS!

Beware of trials factor of choosing LEM over LID after seeing results.

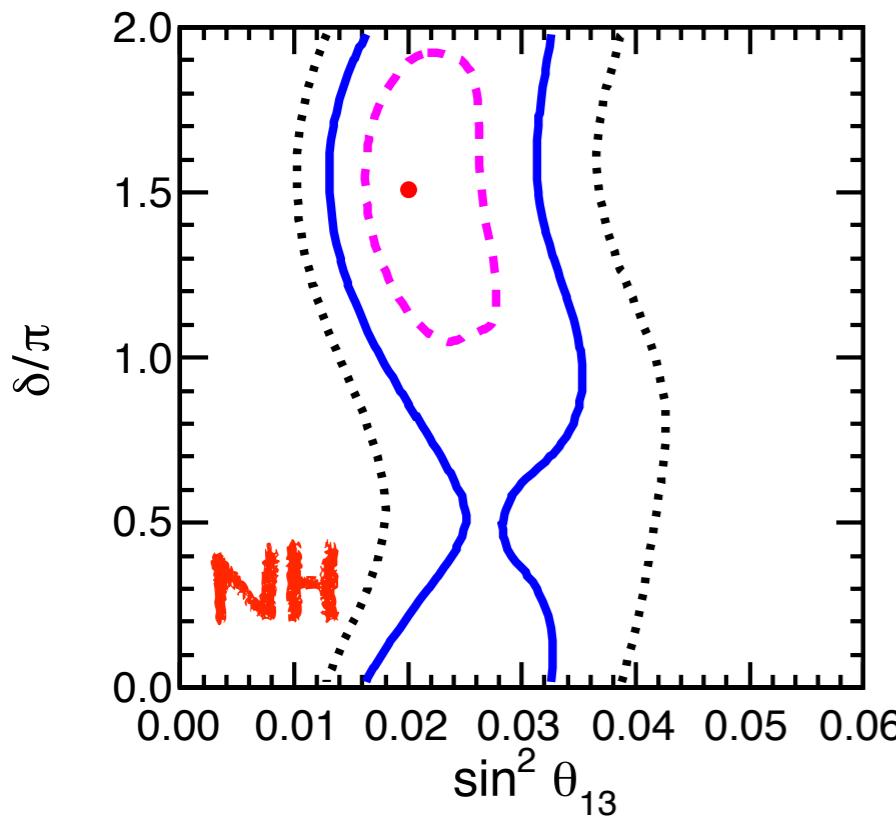


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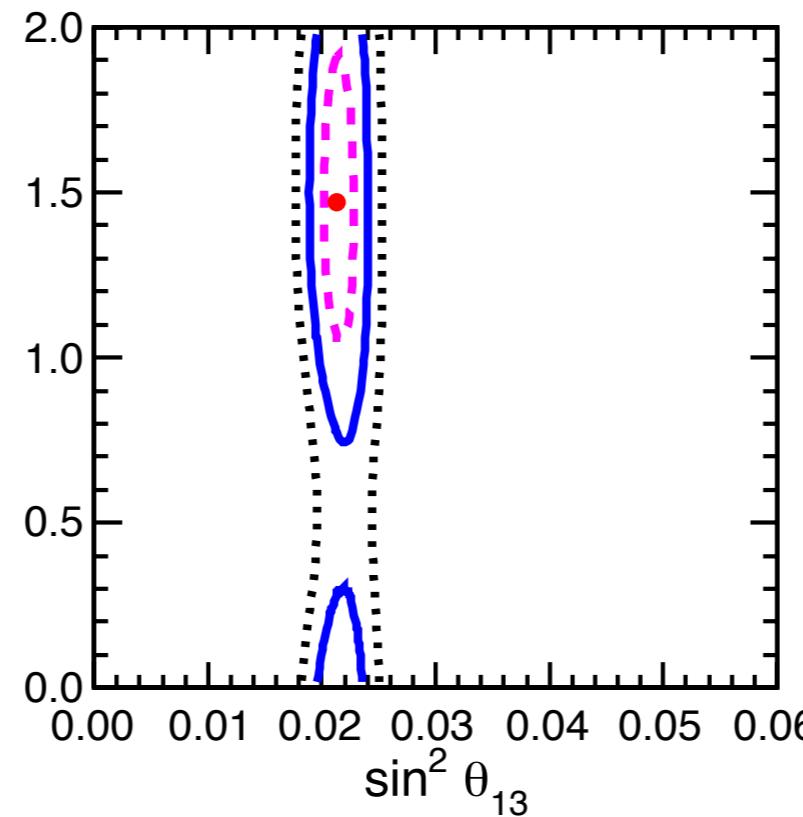
GLOBAL ANALYSIS FOR CP VIOLATION

A. MARRONE (TAUP 2015)

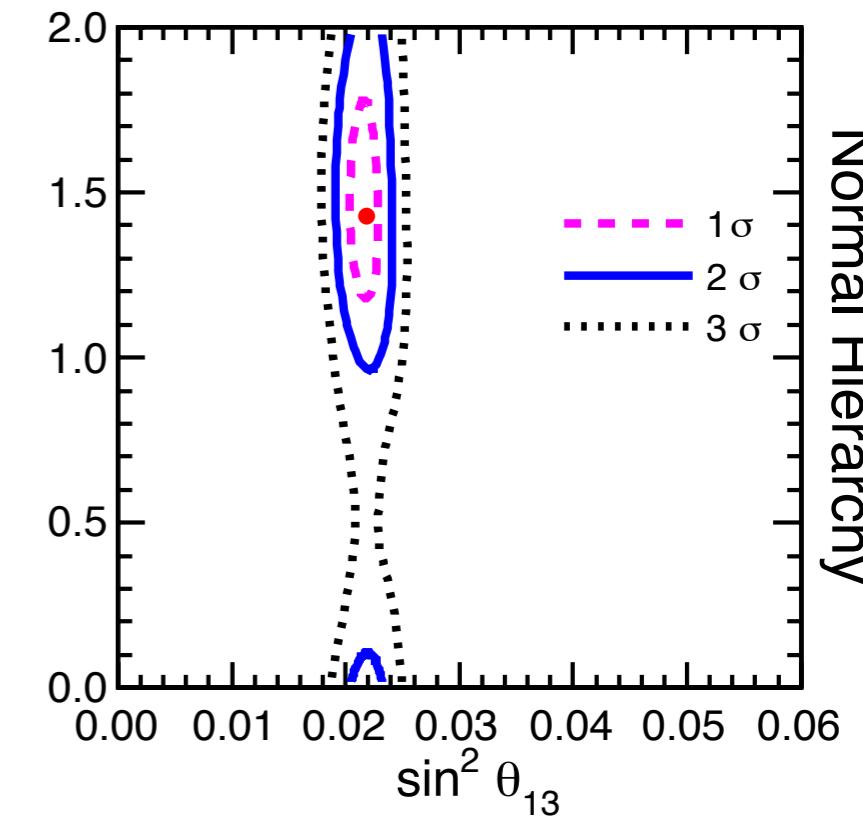
LBL Acc + Solar + KL



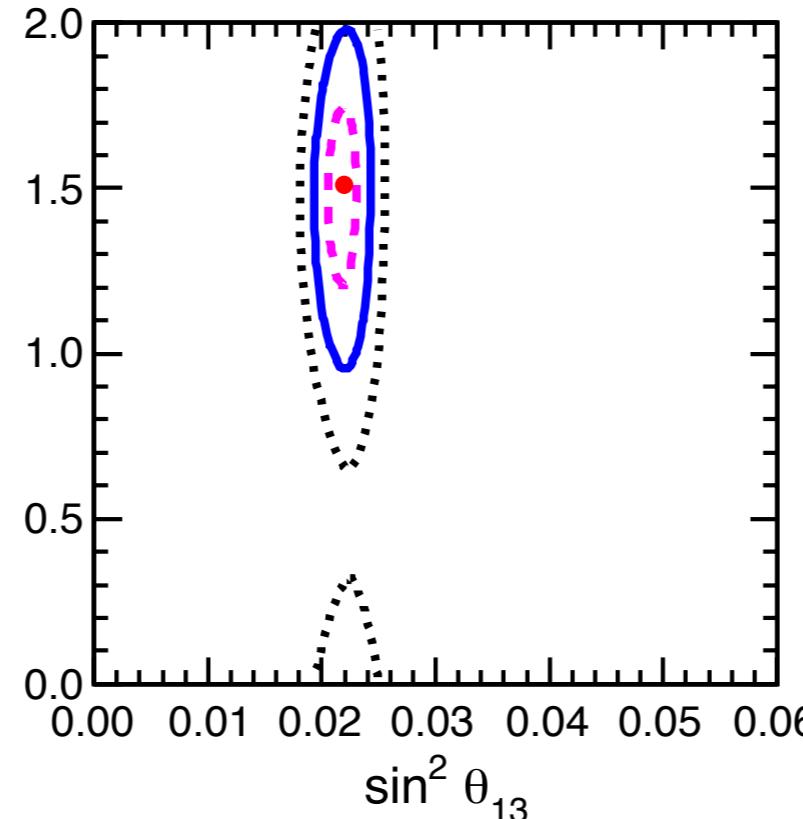
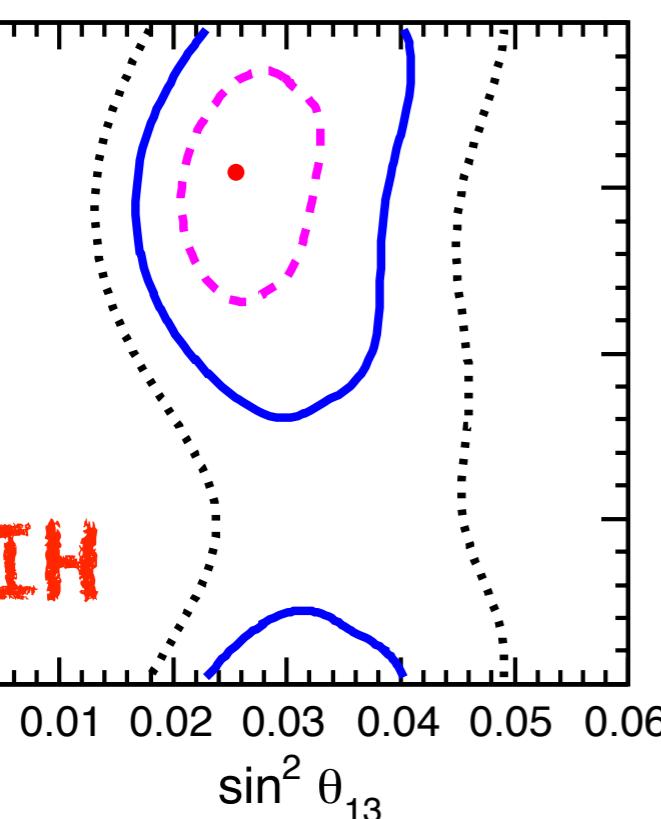
+ SBL Reactors



+ SK Atm



Normal Hierarchy



Inverted Hierarchy

GLOBAL ANALYSIS FOR CP VIOLATION

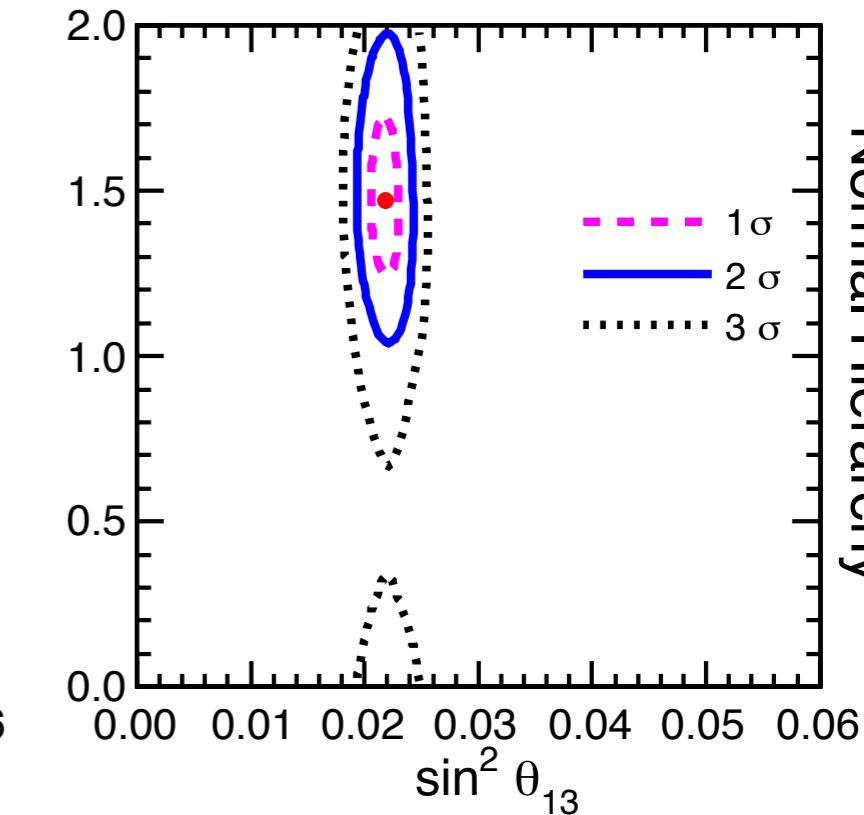
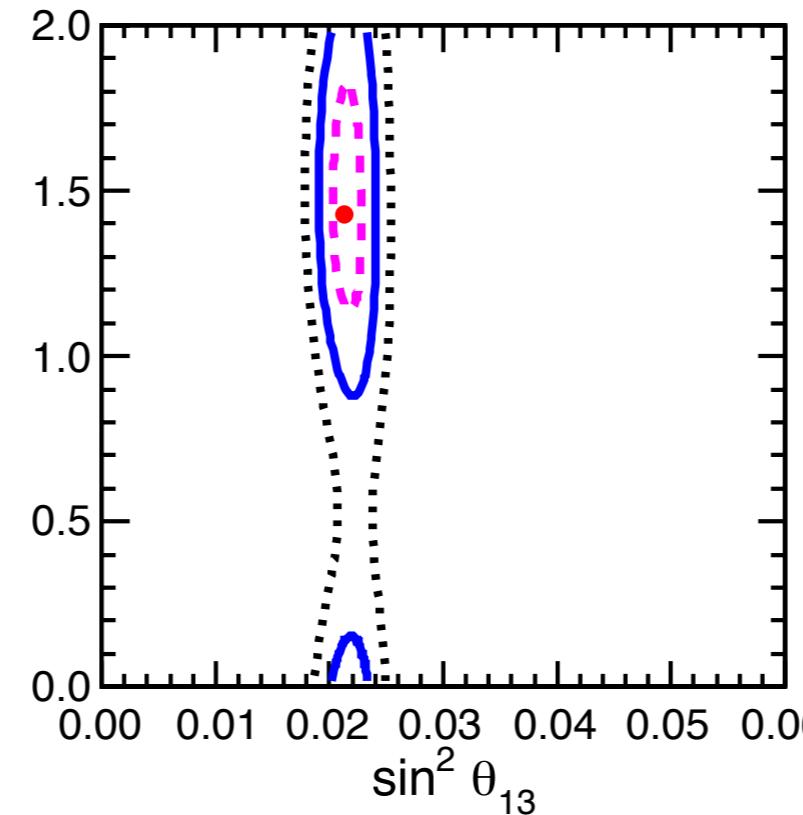
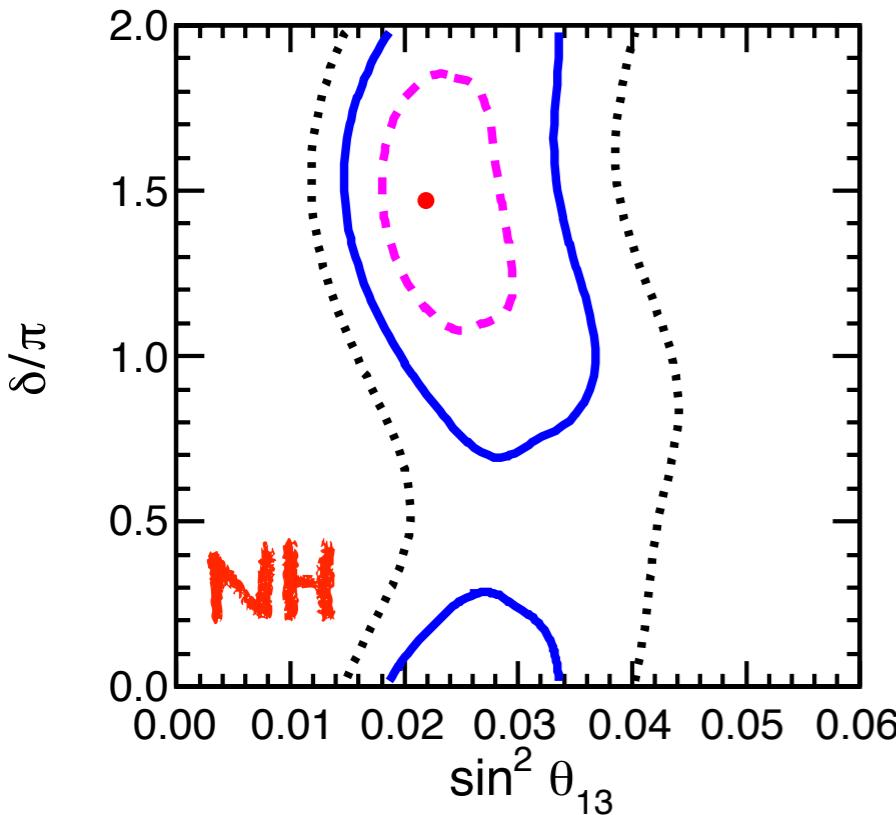
INCLUDES NOVA'S LATEST RESULTS

A. MARRONE (TAUP 2015)

LBL Acc + Solar + KL

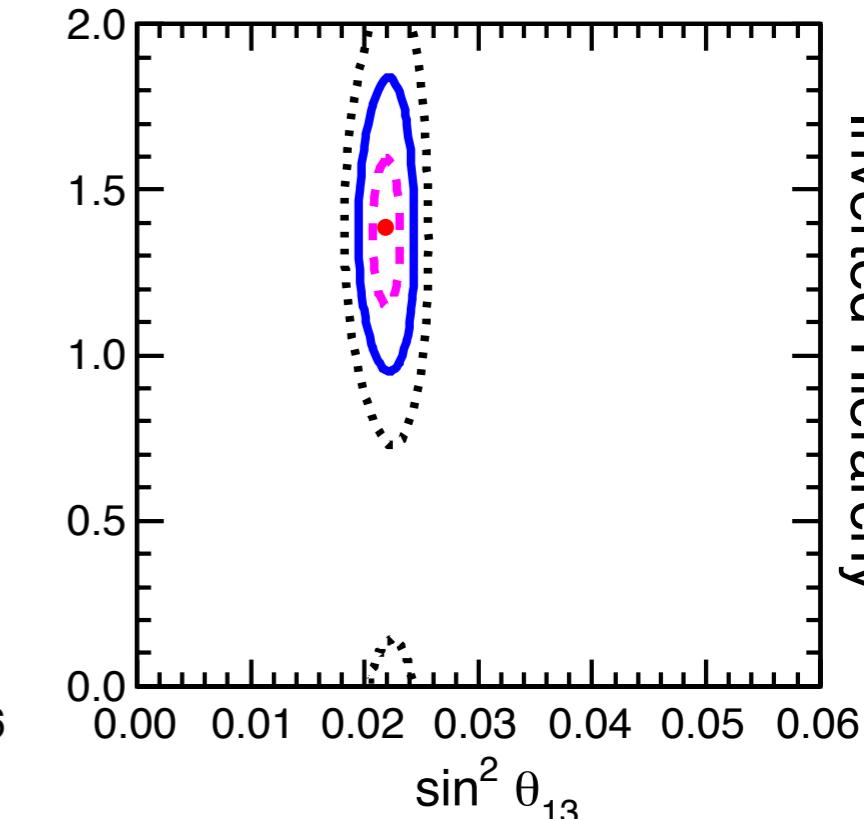
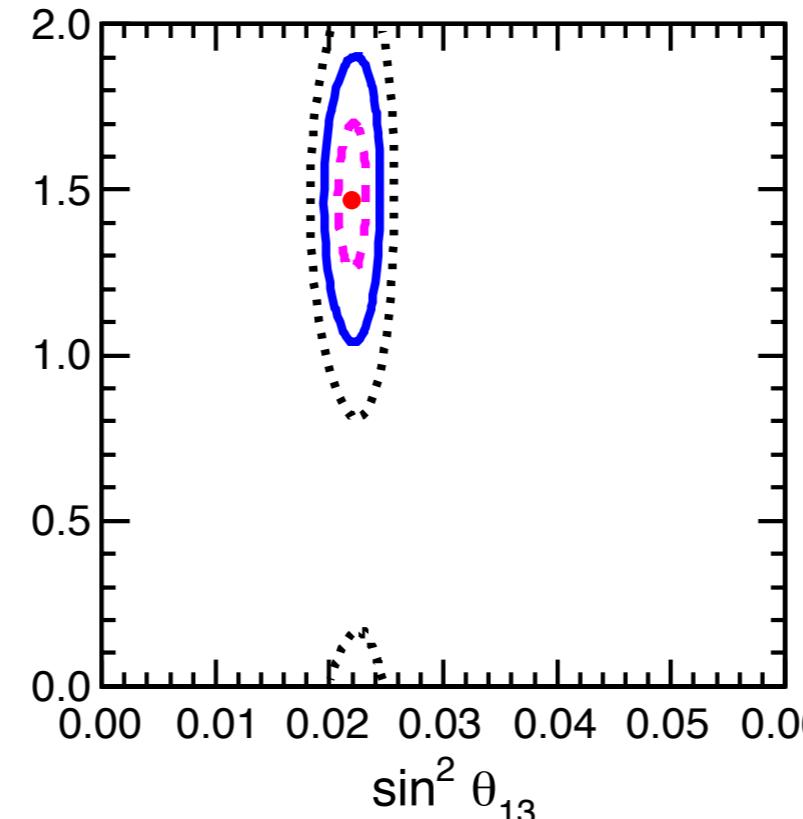
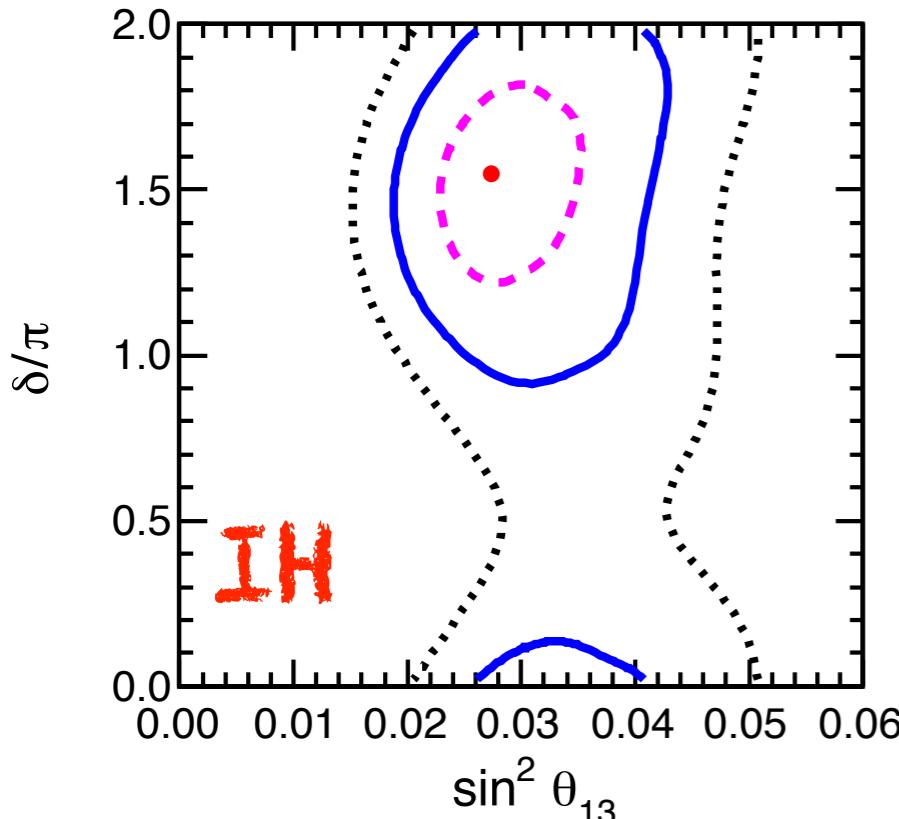
+ SBL Reactors

+ SK Atm



Normal Hierarchy

Inverted Hierarchy

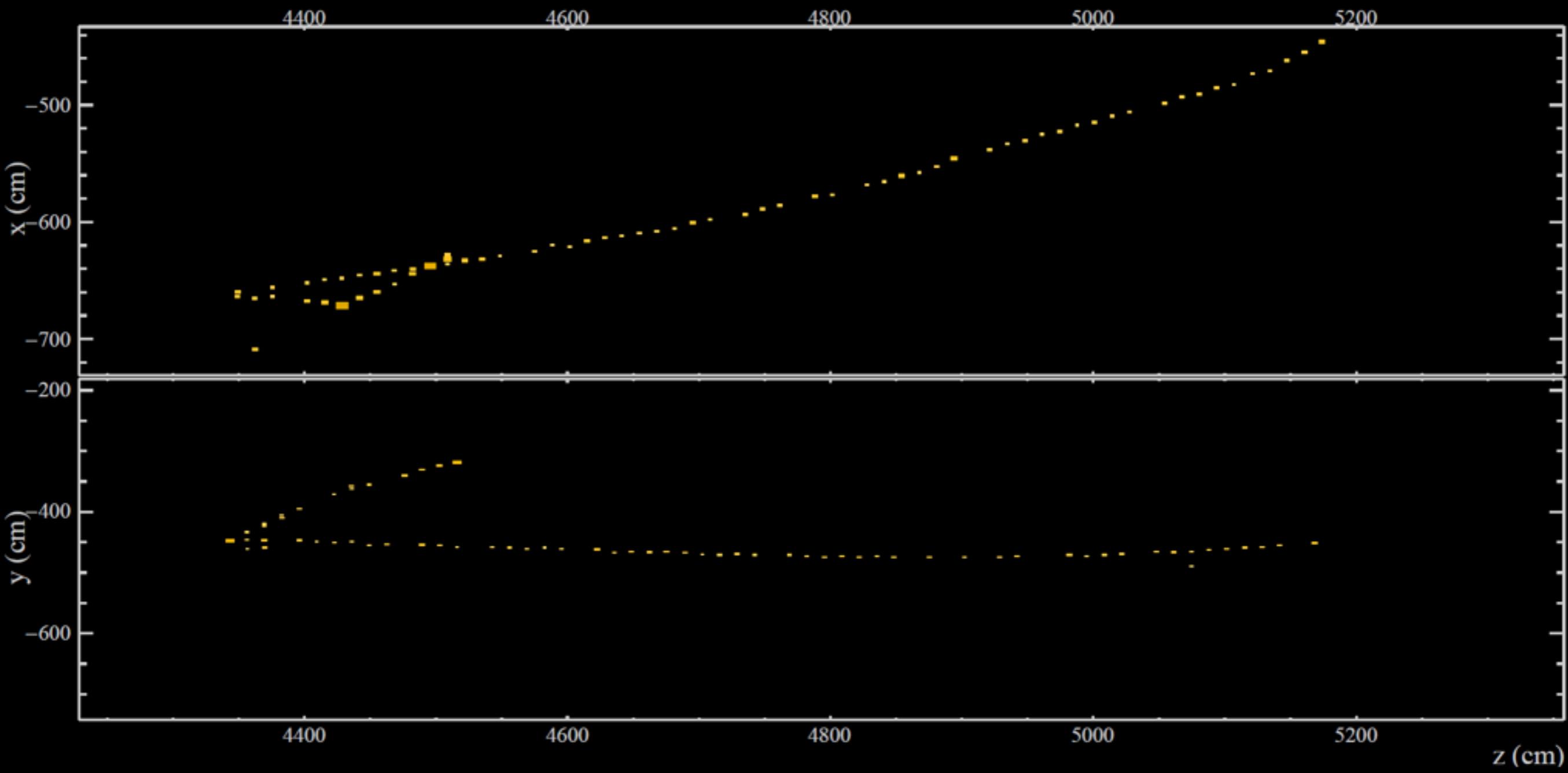


SUMMARY

- NOvA has observed muon neutrino disappearance and electron neutrino appearance with 1/13th of baseline exposure:
 - Obtains 6.5% measurement of atmospheric mass splitting, and θ_{23} measurement consistent with maximal mixing.
 - Observes electron neutrino appearance signal at 3.3σ for primary ν_e selector, 5.5σ for secondary selector.
 - Consistent with hints of a preference for $\pi < \delta_{CP} < 2\pi$ normal mass ordering.
 - In global analysis the preference for $\pi < \delta_{CP} < 2\pi$ is clear.
 - Stay tuned for doubling of the data set by next summer!

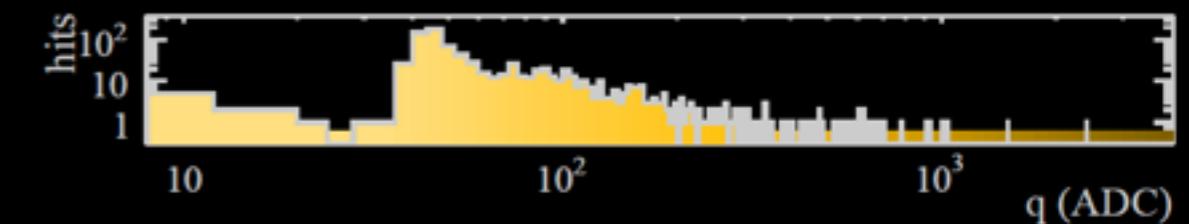
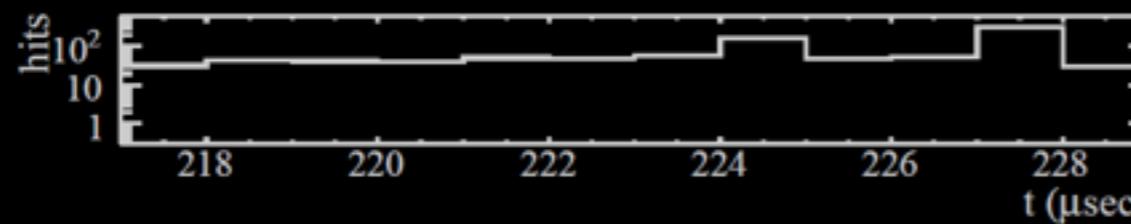
BACKUP

MUON NEUTRINO CANDIDATE

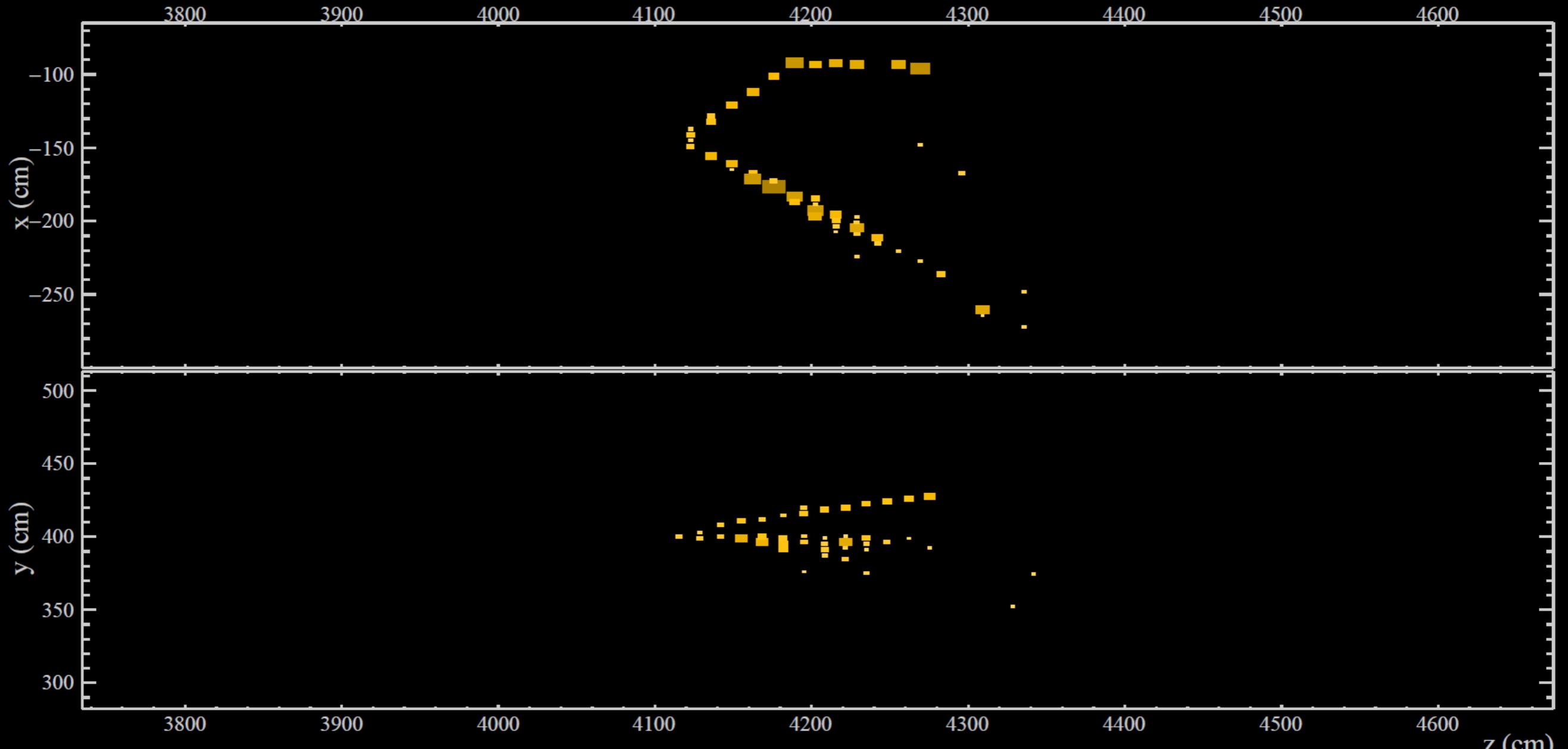


NOvA - FNAL E929

Run: 18791 / 48
Event: 765587 / --
UTC Fri Jan 30, 2015
07:19:18.516289184

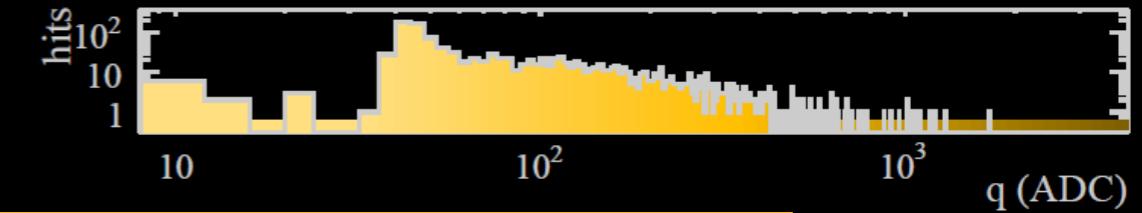
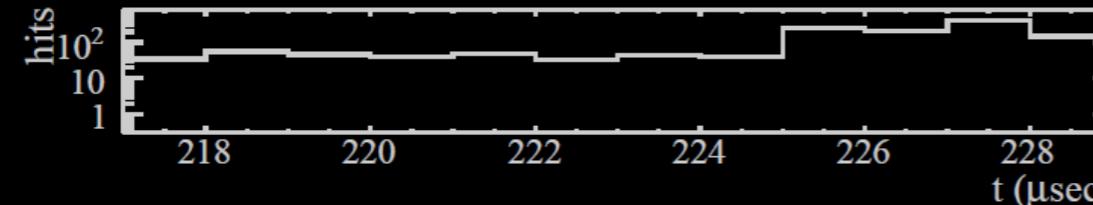


ELECTRON NEUTRINO CANDIDATE

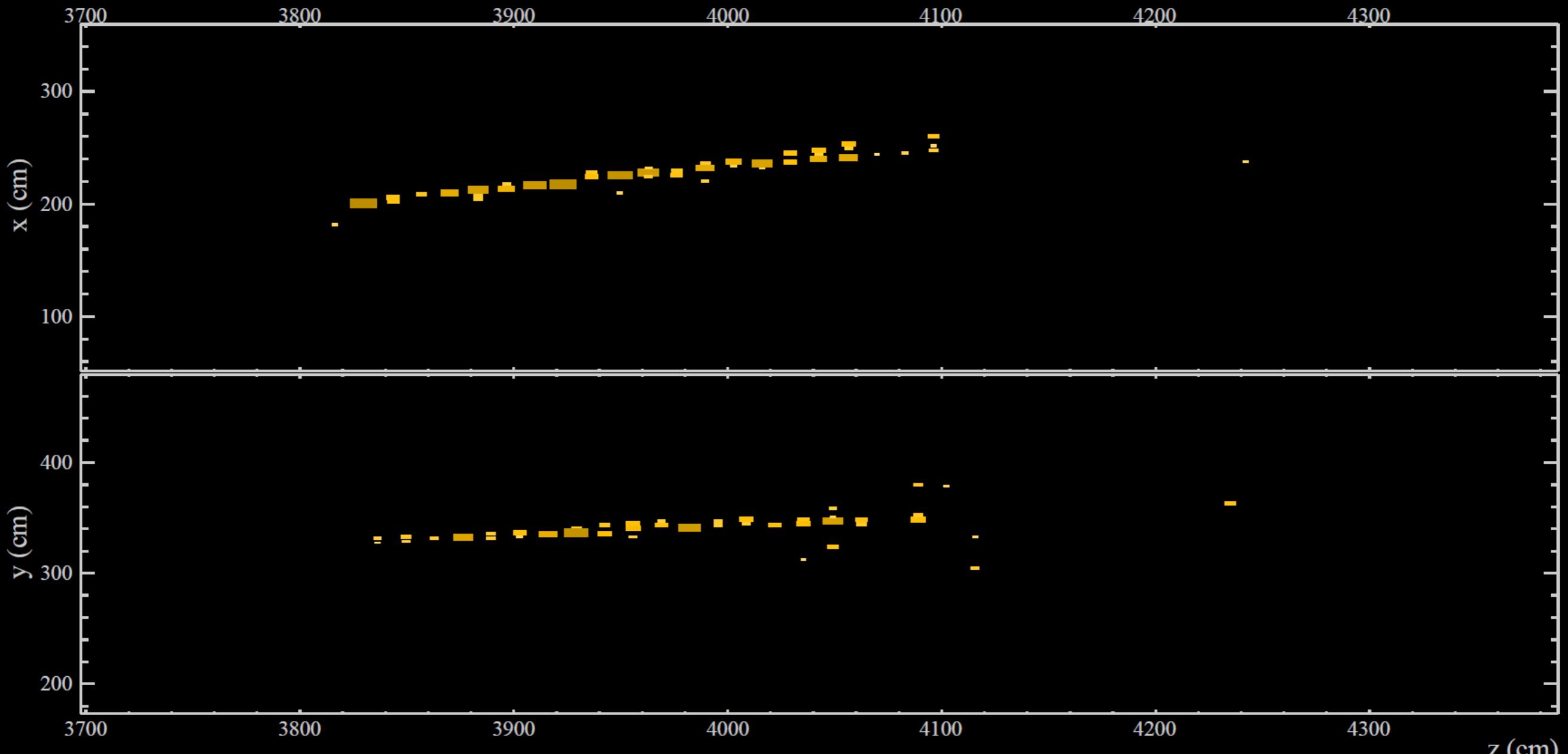


NOvA - FNAL E929

Run: 19578 / 5
Event: 98069 / -
UTC Thu May 14, 2015
17:55:39.044985484

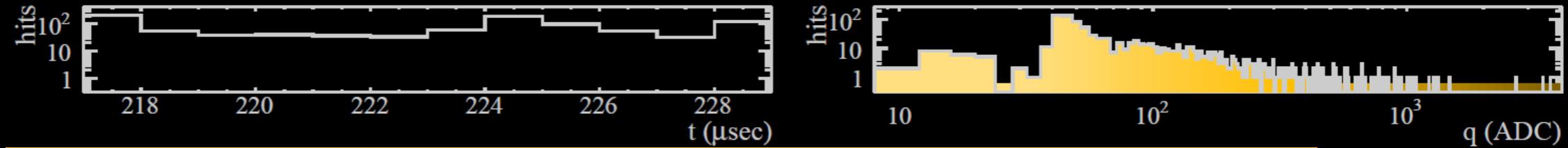


ELECTRON NEUTRINO CANDIDATE



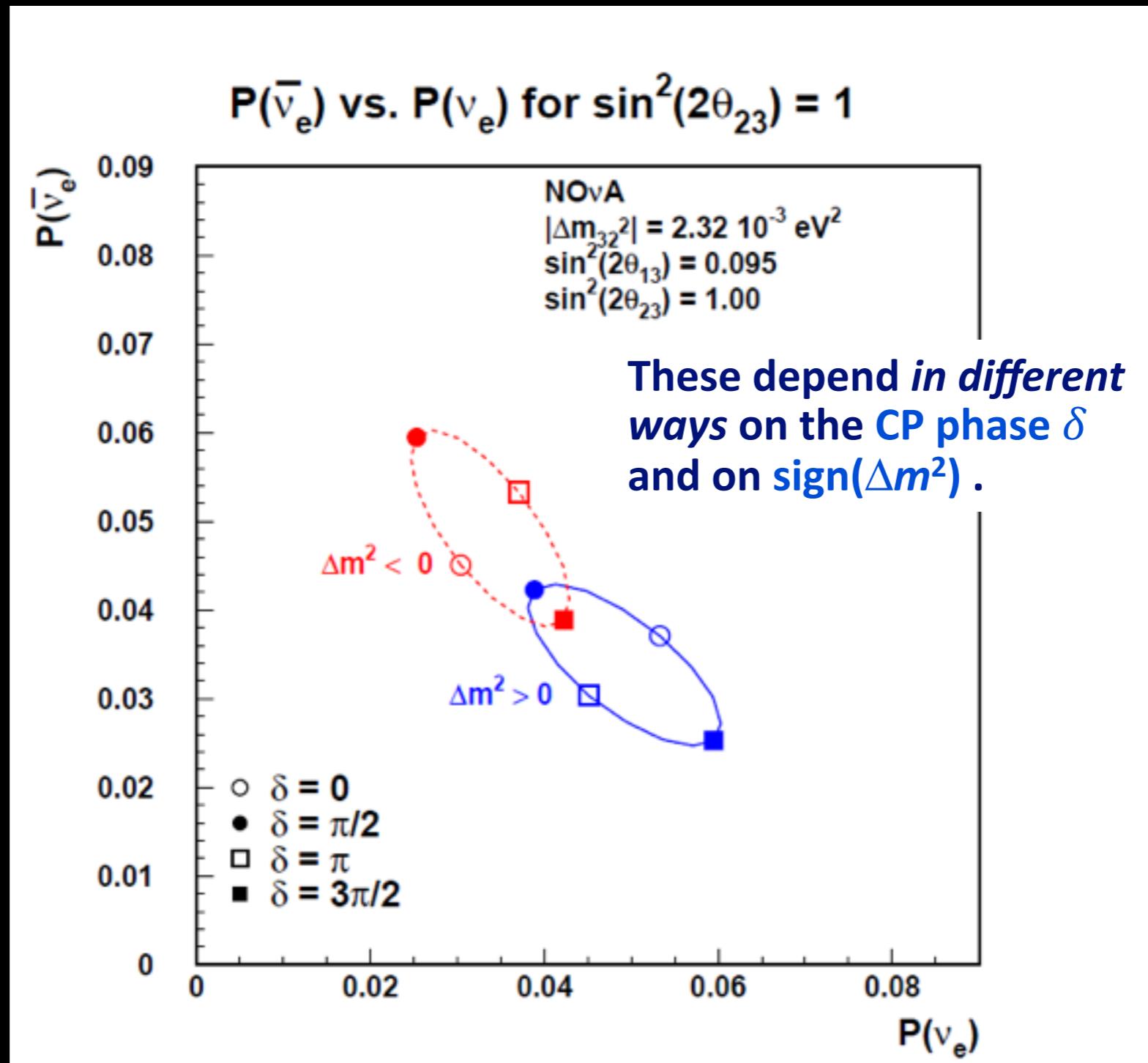
NOvA - FNAL E929

Run: 17103 / 7
Event: 27816 / --
UTC Wed Sep 3, 2014
10:04:58.572014784



NOVA PHYSICS

NO ν A will measure: $P(\nu_\mu \rightarrow \nu_e)$ at 2 GeV and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2 GeV



- Large θ_{13} is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

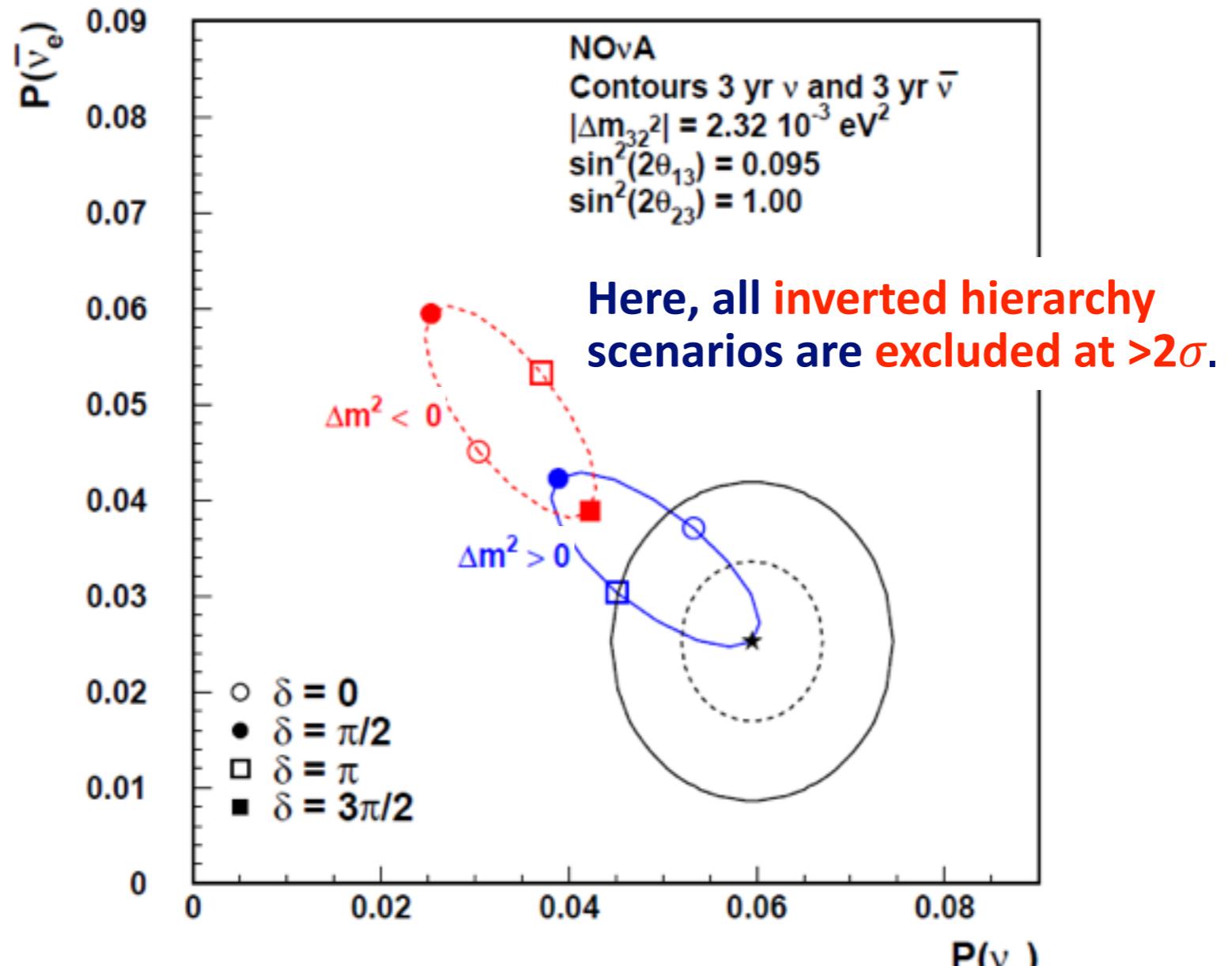
NOVA PHYSICS

Example NO ν A result...

Our data will yield allowed regions in $P(\bar{\nu}_e)$ vs. $P(\nu_e)$ space

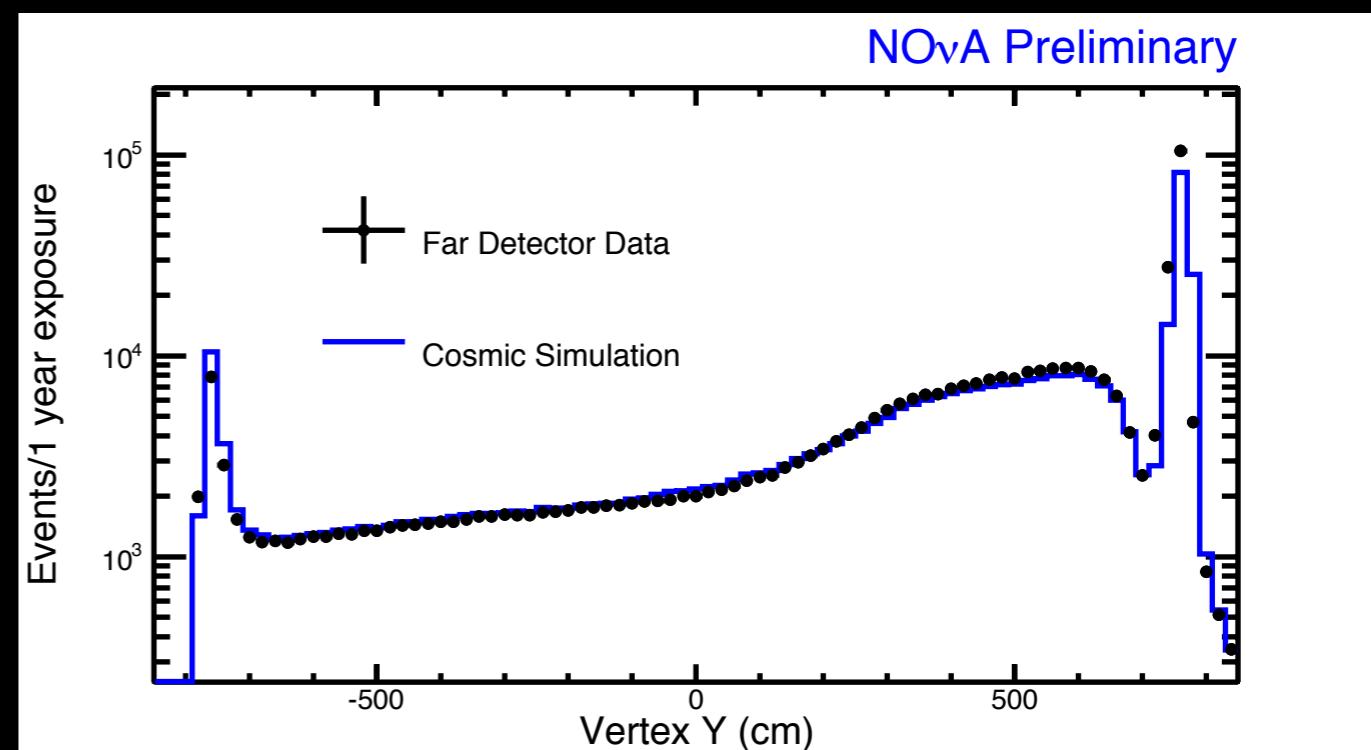
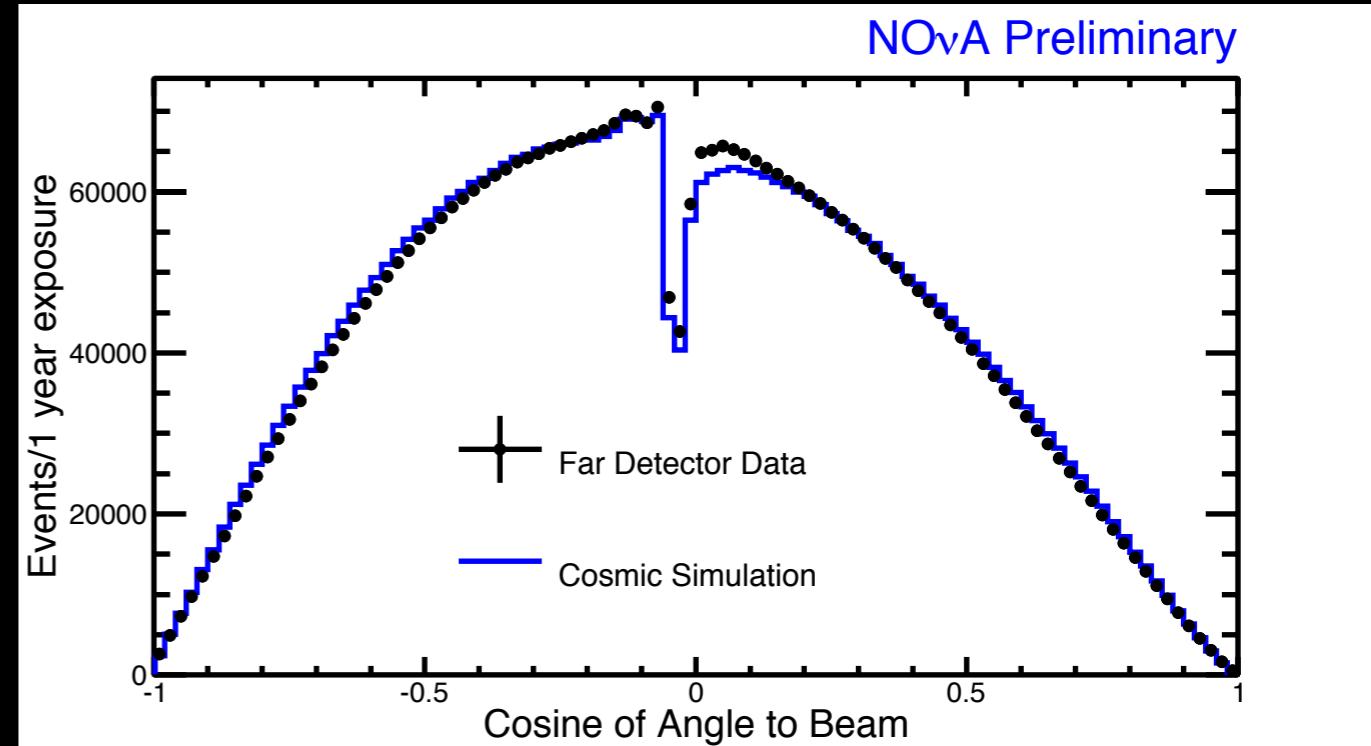
(3 yr + 3 yr possibility shown)

1 and 2 σ Contours for Starred Point



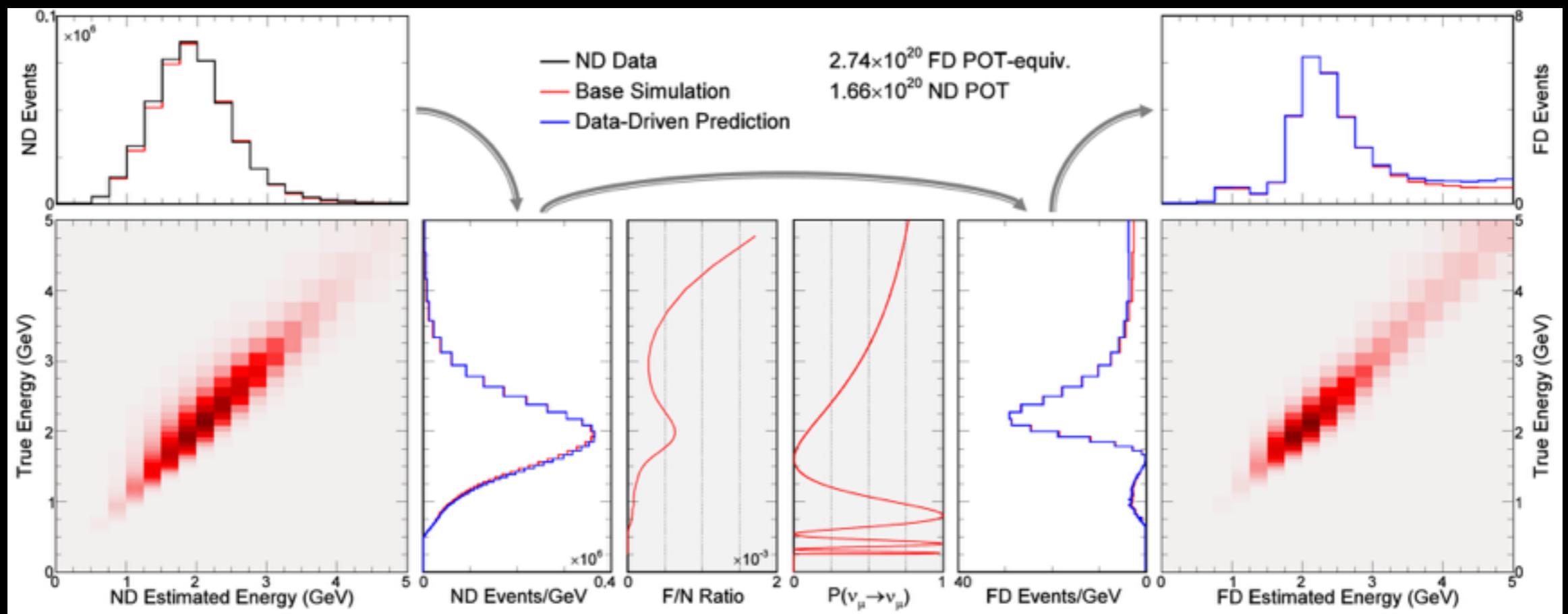
COSMIC BACKGROUND DATA

- We take data independent of the beam spills for calibration and cosmic background studies.
- These data is well described by CRY simulation.

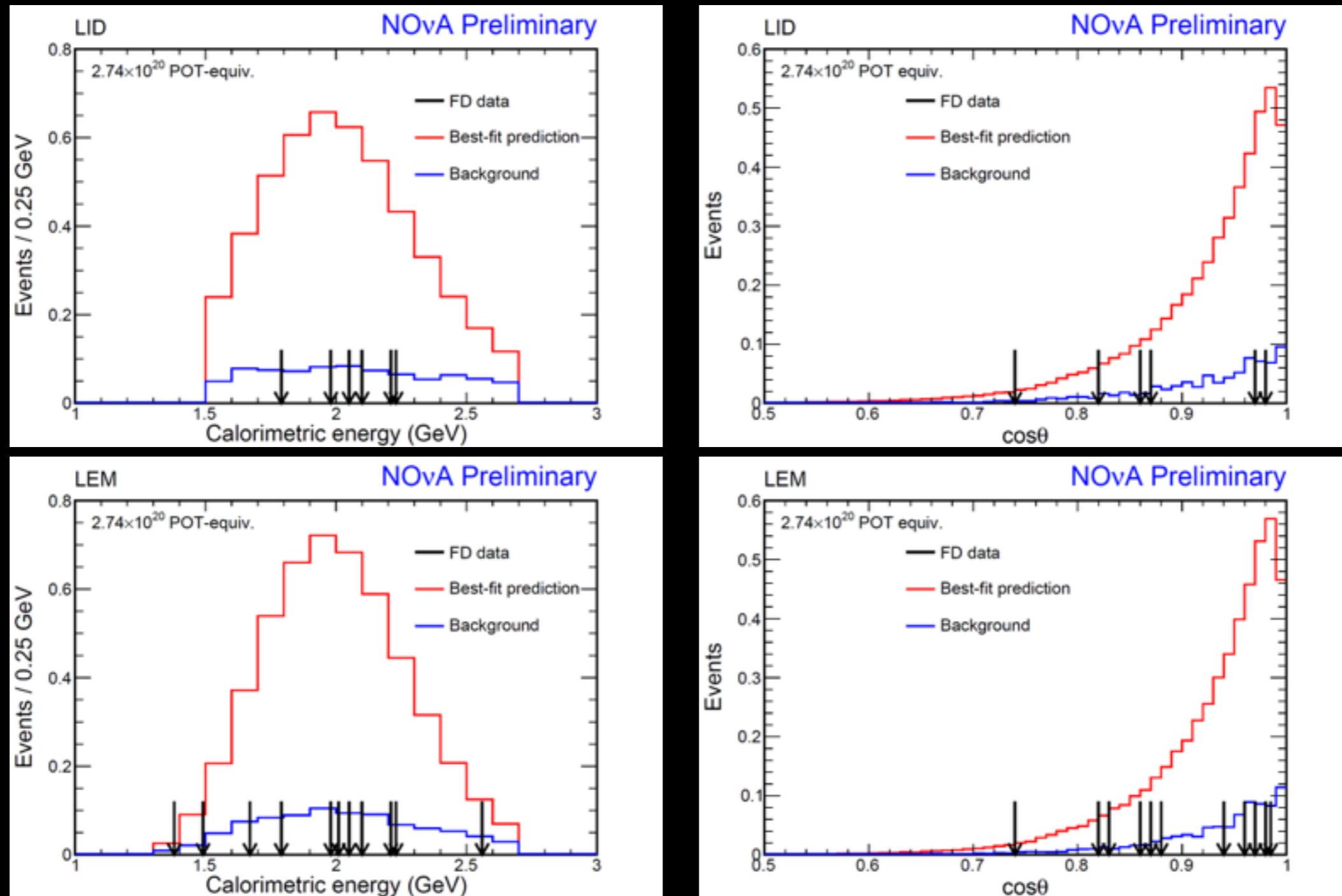


DATA-DRIVEN FAR DETECTOR MUON NEUTRINO PREDICTION

- Estimate the underlying true energy distribution of selected ND events.
- Multiply by expected Far/Near event ratio and $\nu_\mu \rightarrow \nu_\mu$ oscillation probability as a function of true energy.
- Convert FD true energy distribution into predicted FD reconstructed energy distribution.
- Systematic uncertainties assessed by varying all MC-based steps.

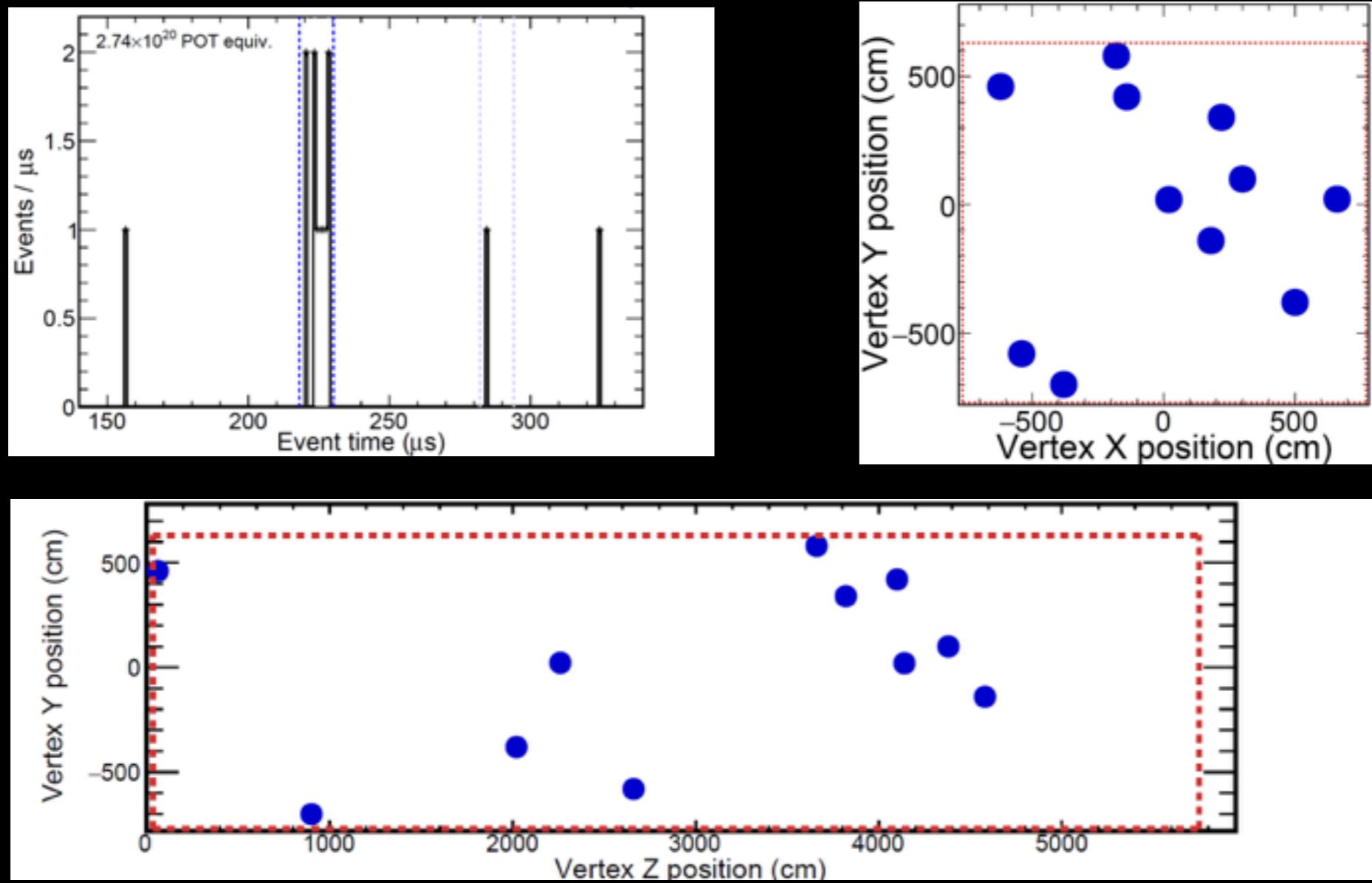


ENERGY AND ANGULAR DISTRIBUTIONS OF ELECTRON NEUTRINO CANDIDATES



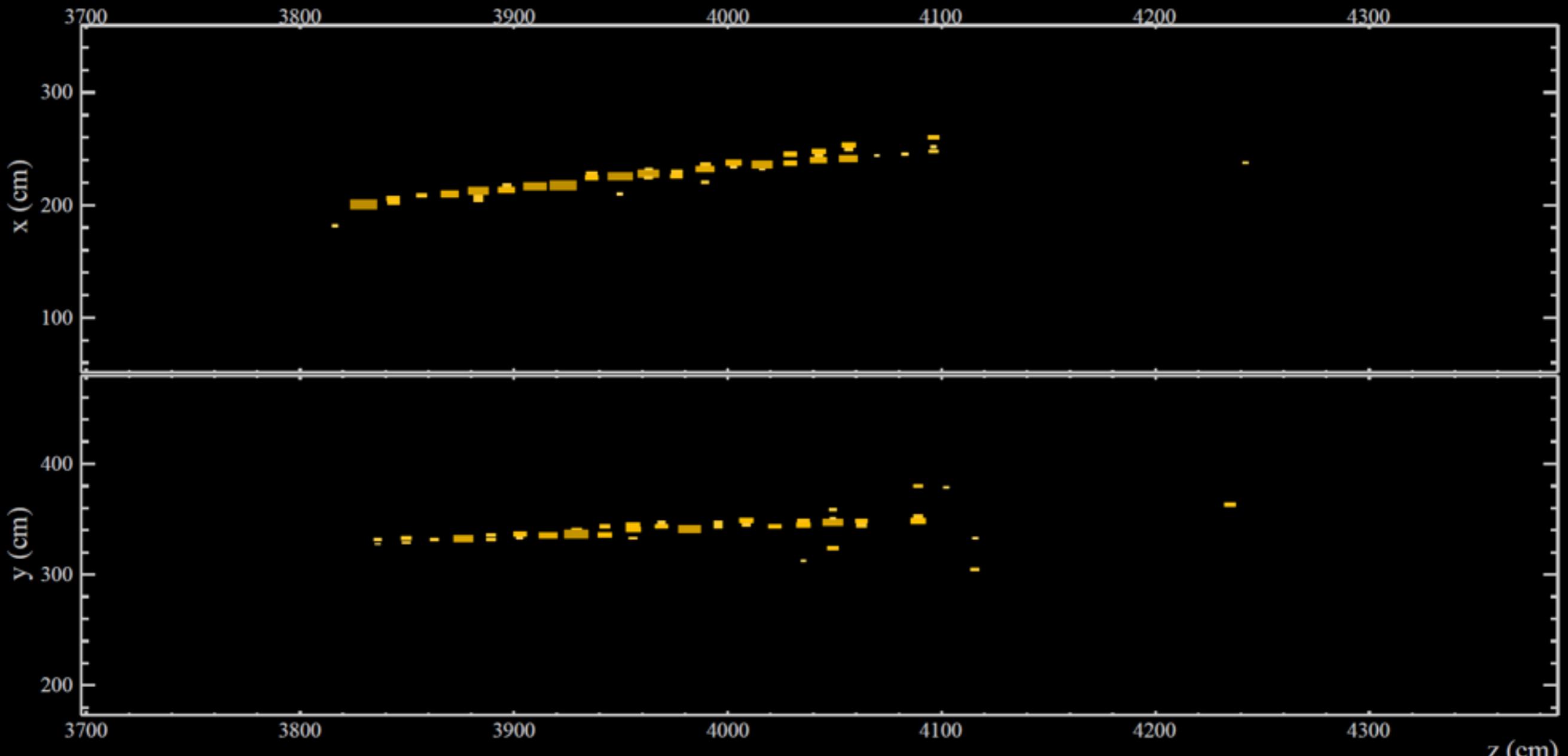
ALL 11 EVENTS ARE REASONABLY DISTRIBUTED IN ENERGY AND ANGLE

TIMING AND VERTEX POSITION DISTRIBUTIONS OF ELECTRON NEUTRINO CANDIDATES



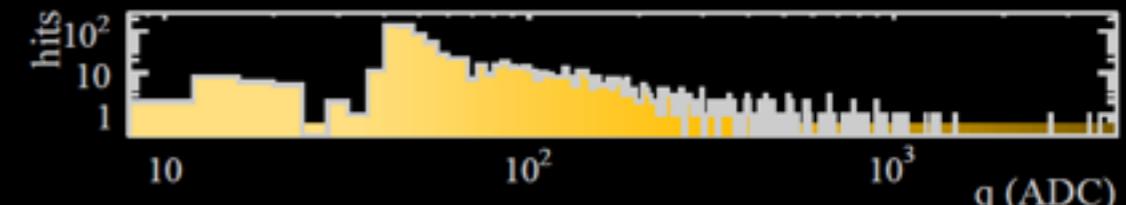
ALL 11 EVENTS ARE REASONABLY DISTRIBUTED IN TIME AND SPACE

ELECTRON NEUTRINO CANDIDATE

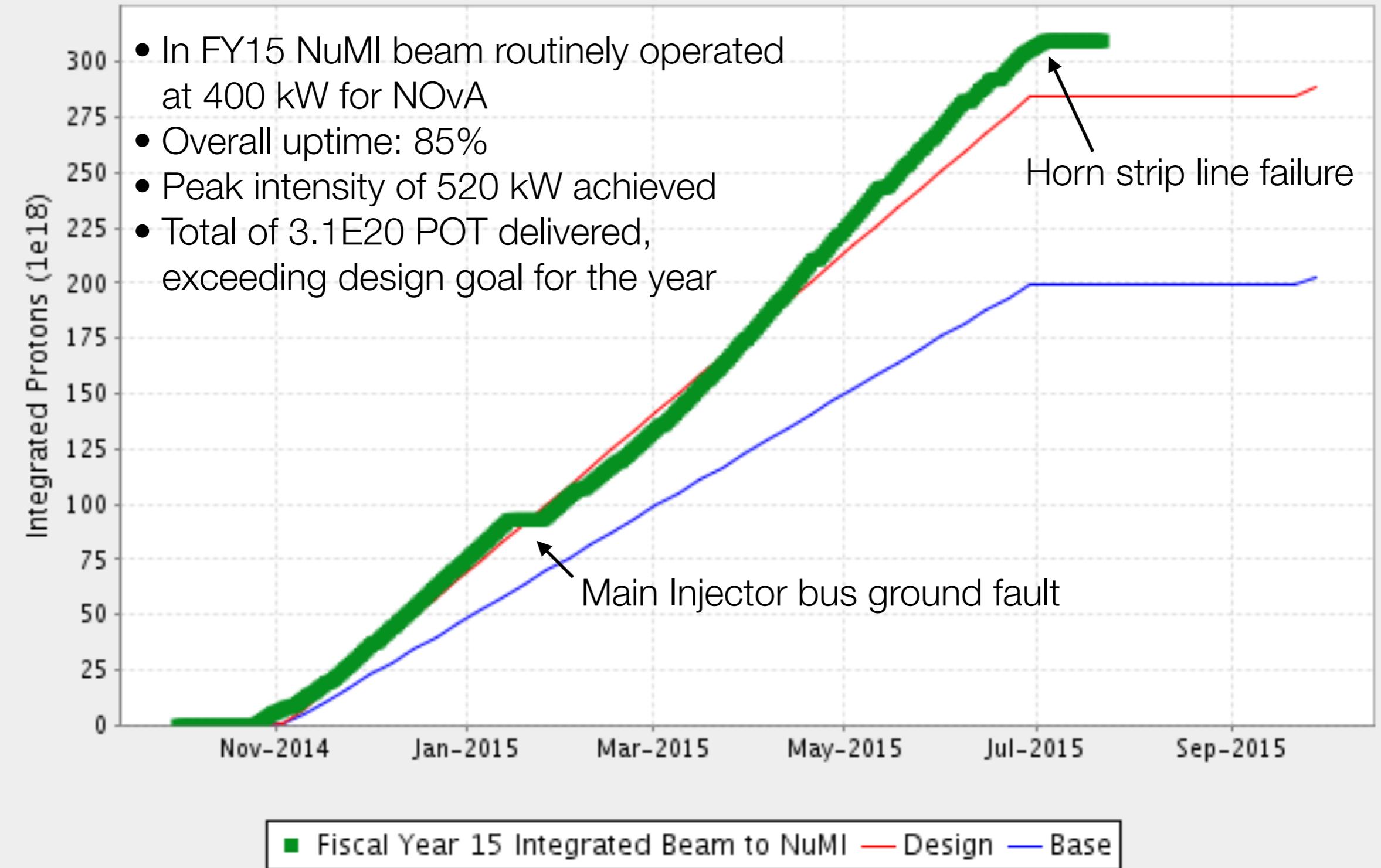


NOvA - FNAL E929

Run: 17103 / 7
Event: 27816 / -
UTC Wed Sep 3, 2014
10:04:58.572014784



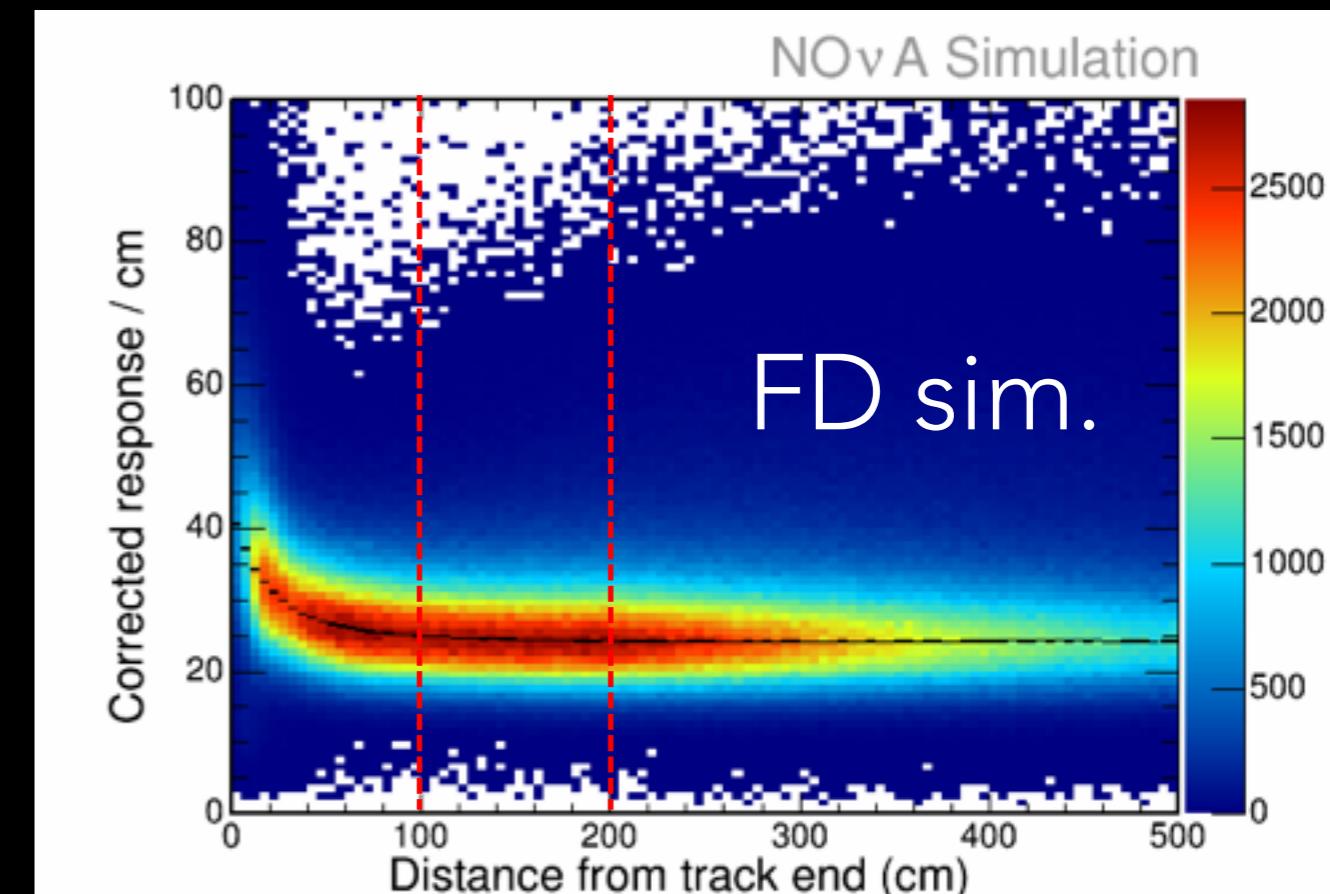
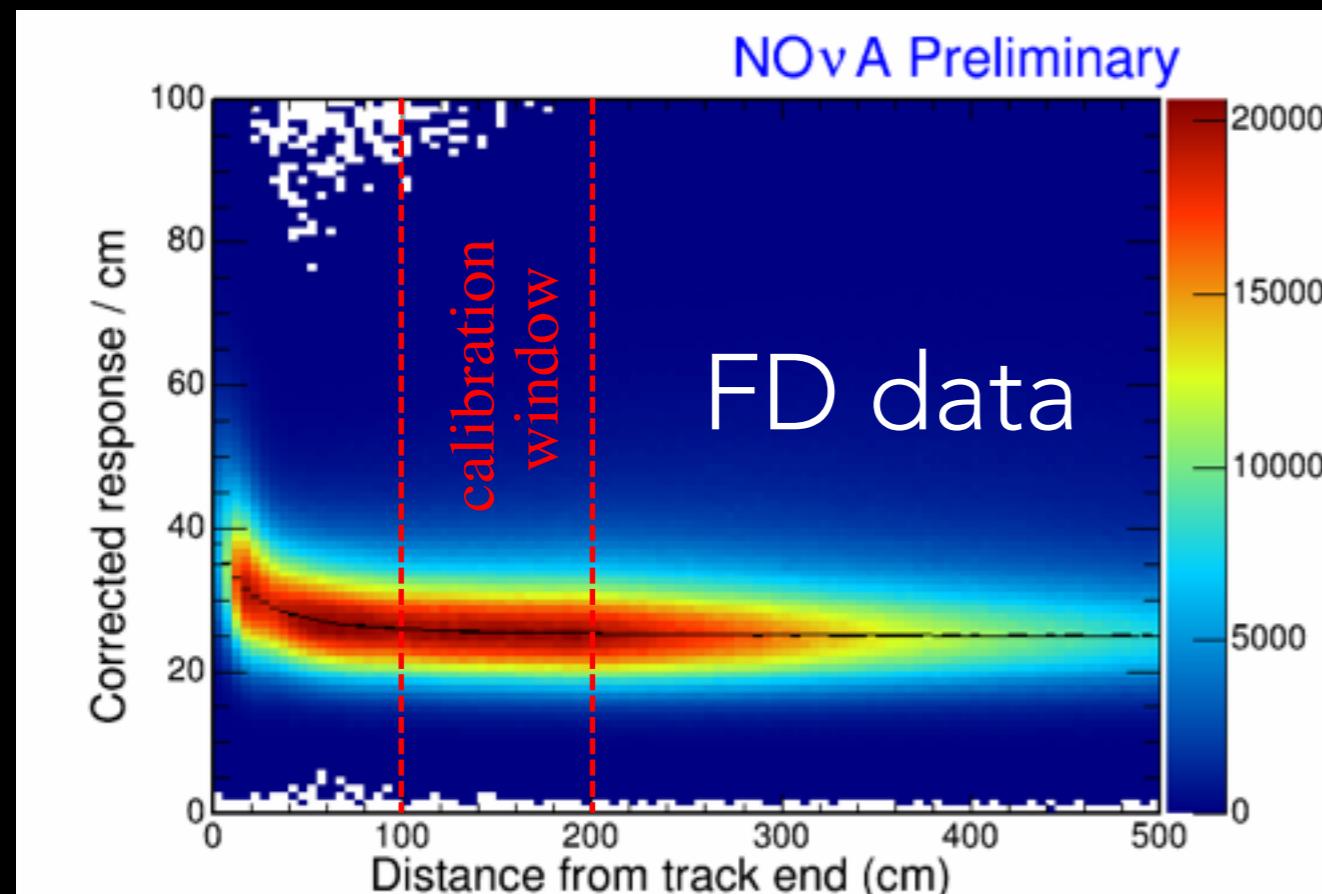
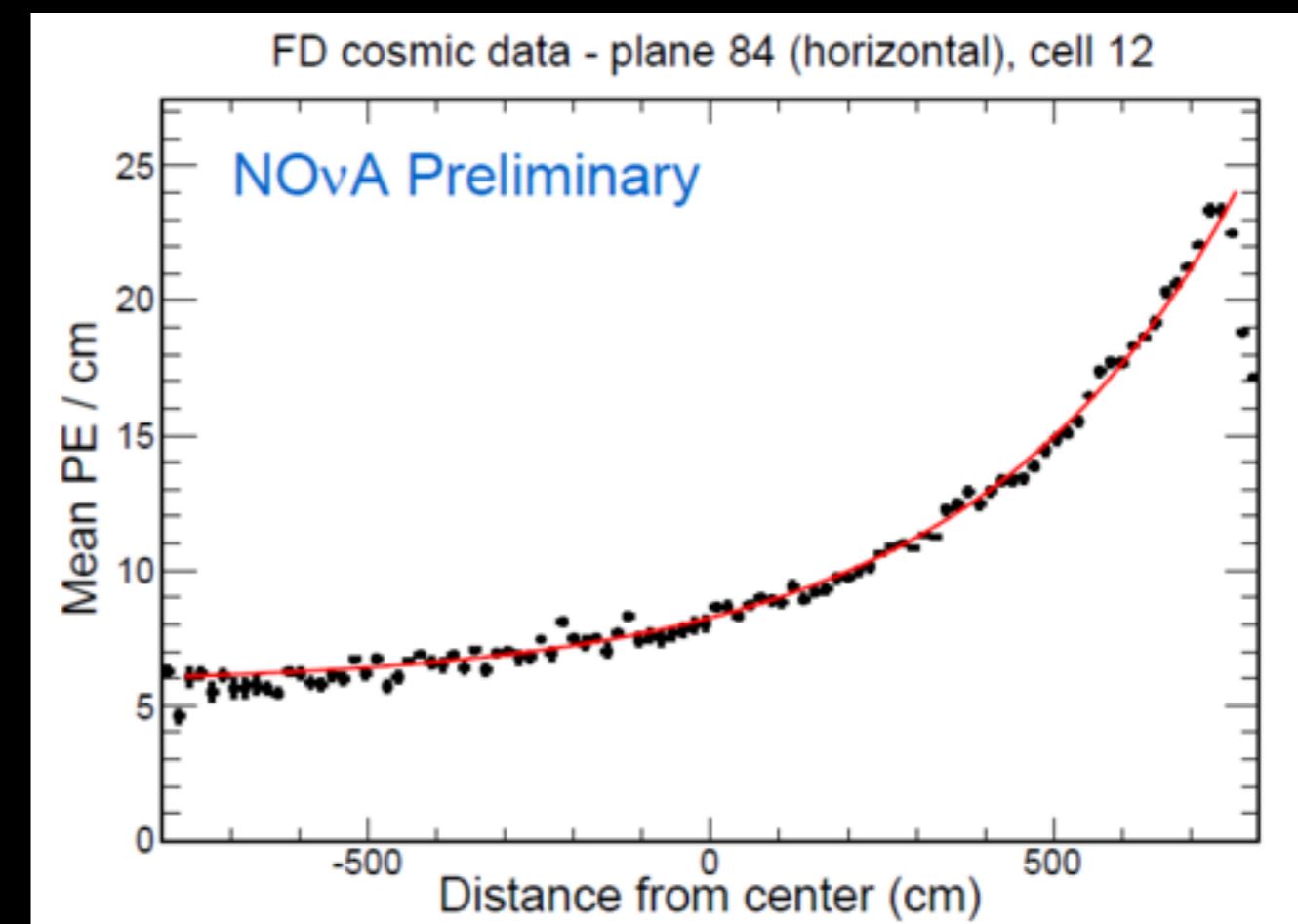
FY15 Integrated Beam to NuMI



US FY2015 NUMI BEAM
PERFORMANCE

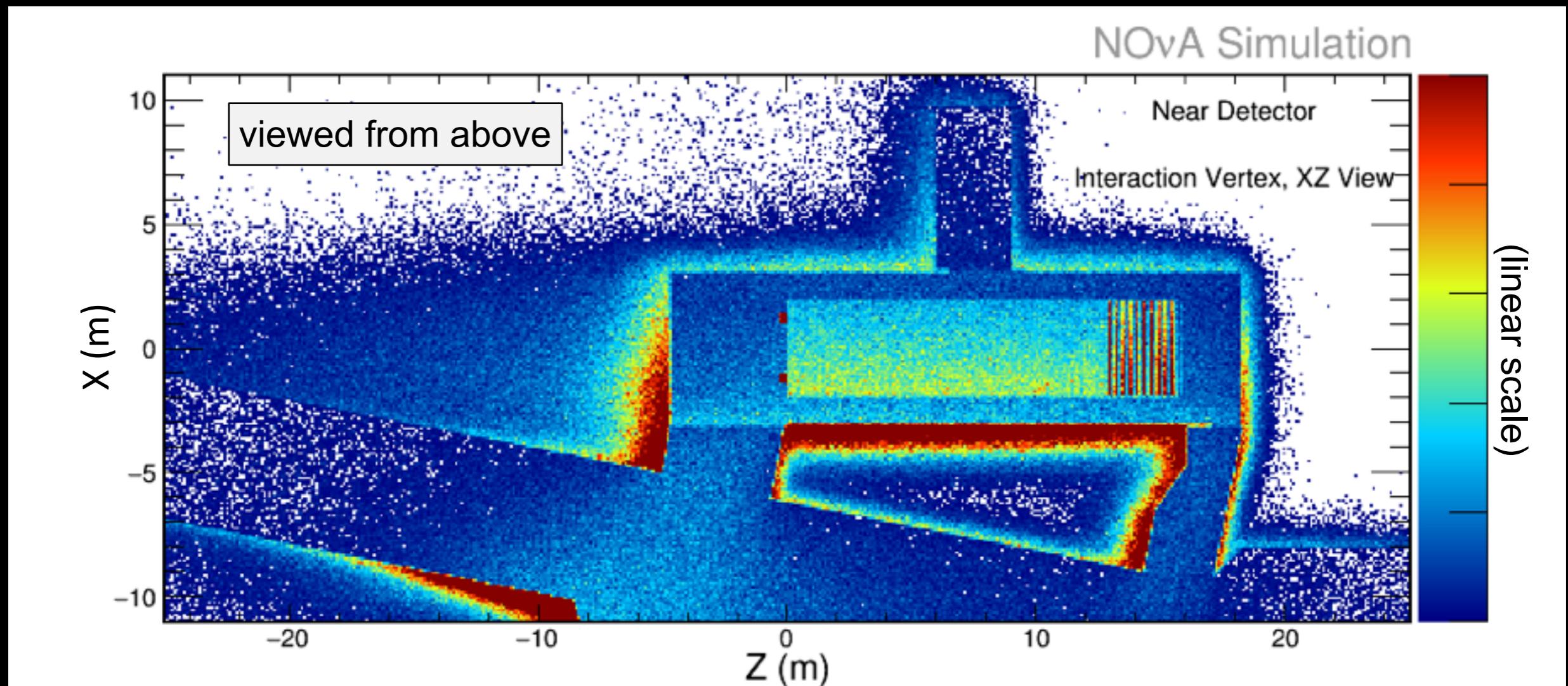
CALIBRATION

- Biggest effect that needs correction is attenuation in the WLS fiber.
- Light levels drop by a factor of 8 across a FD cell.
- Stopping muons provide a standard candle for setting absolute energy scale.



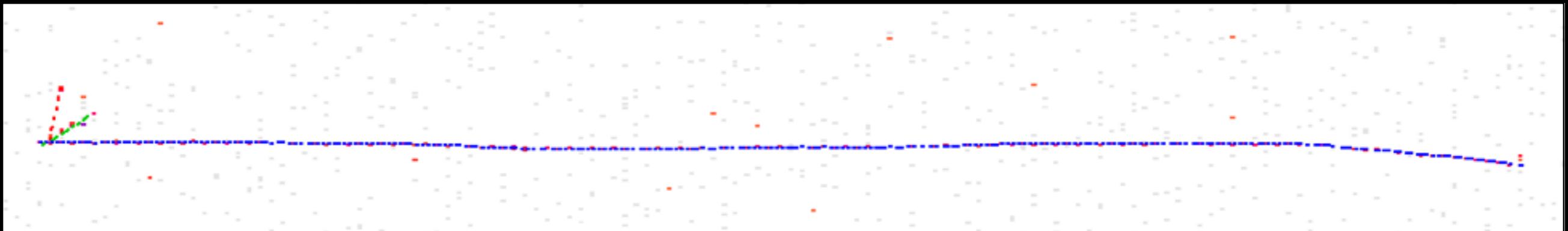
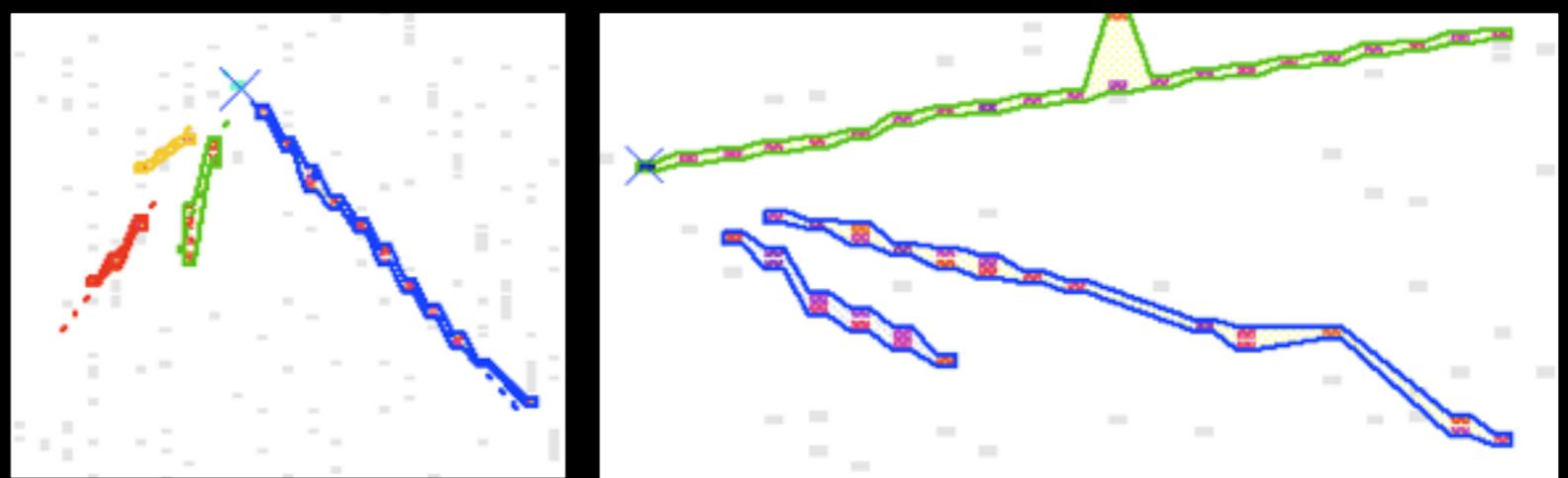
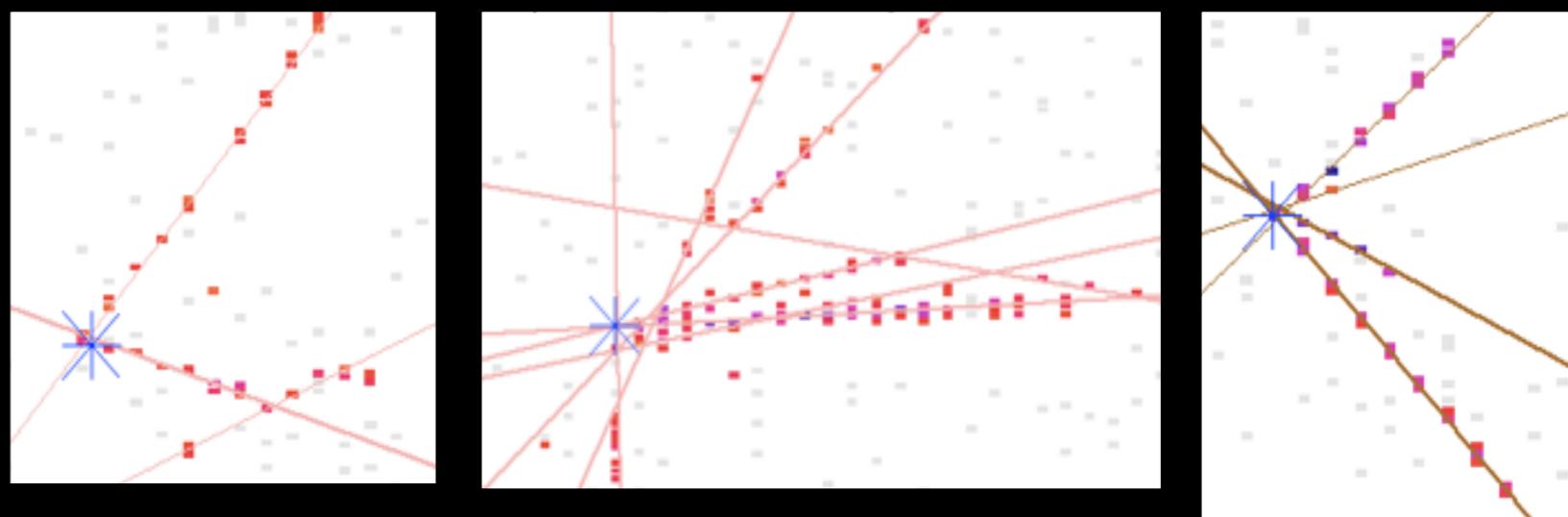
NOVA SIMULATION

- Beam hadron production, propagation; neutrino flux: FLUKA/FLUGG
- Cosmic ray flux: CRY
- Neutrino interactions and FSI modeling: GENIE
- Detector simulation: GEANT4
- Readout electronics and DAQ: Custom simulation routines



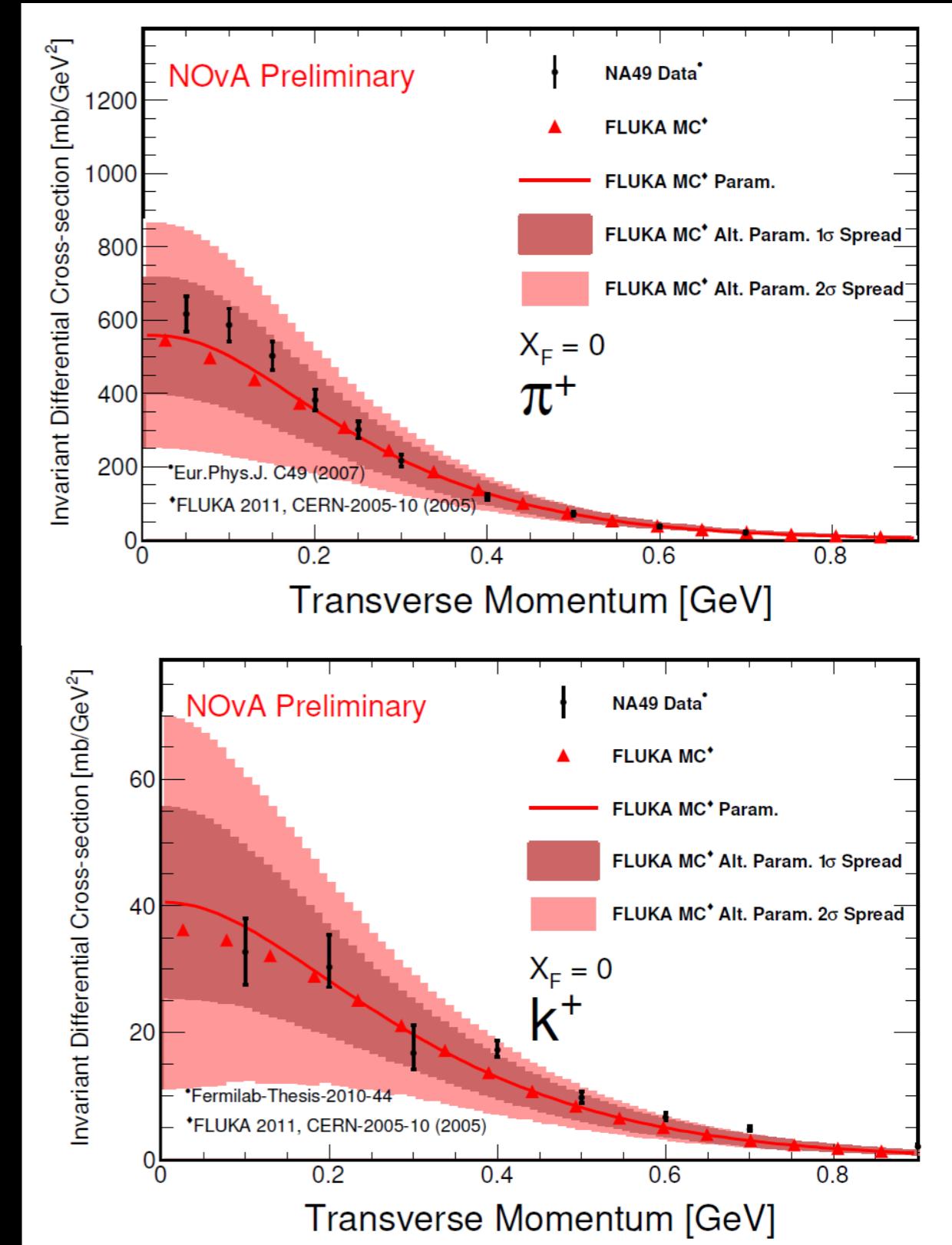
NOVA RECONSTRUCTION

- Vertexing: Find lines of energy depositions w/ Hough transform. CC events: 11cm resolution.
- Clustering: Find clusters in angular space around vertex. Merge views via topology and prong dE/dx .
- Tracking: Trace particle trajectories with Kalman filter tracker.
- Also have a cosmic ray tracker: lightweight, very fast, and useful for large calibration samples and online monitoring tools.



FLUX UNCERTAINTIES

- Full beam geometry simulated with Fluka(11.2c.0) and Flugg(2009_3).
- Hadron production errors come from comparison of NA49 thin target data with simulation.
- Focusing and beam line errors include:
 - Horn current miscalibration
 - Horn position/misalignment
 - Current distribution
 - Beam position on target
 - Proton beam spot size
 - Target position

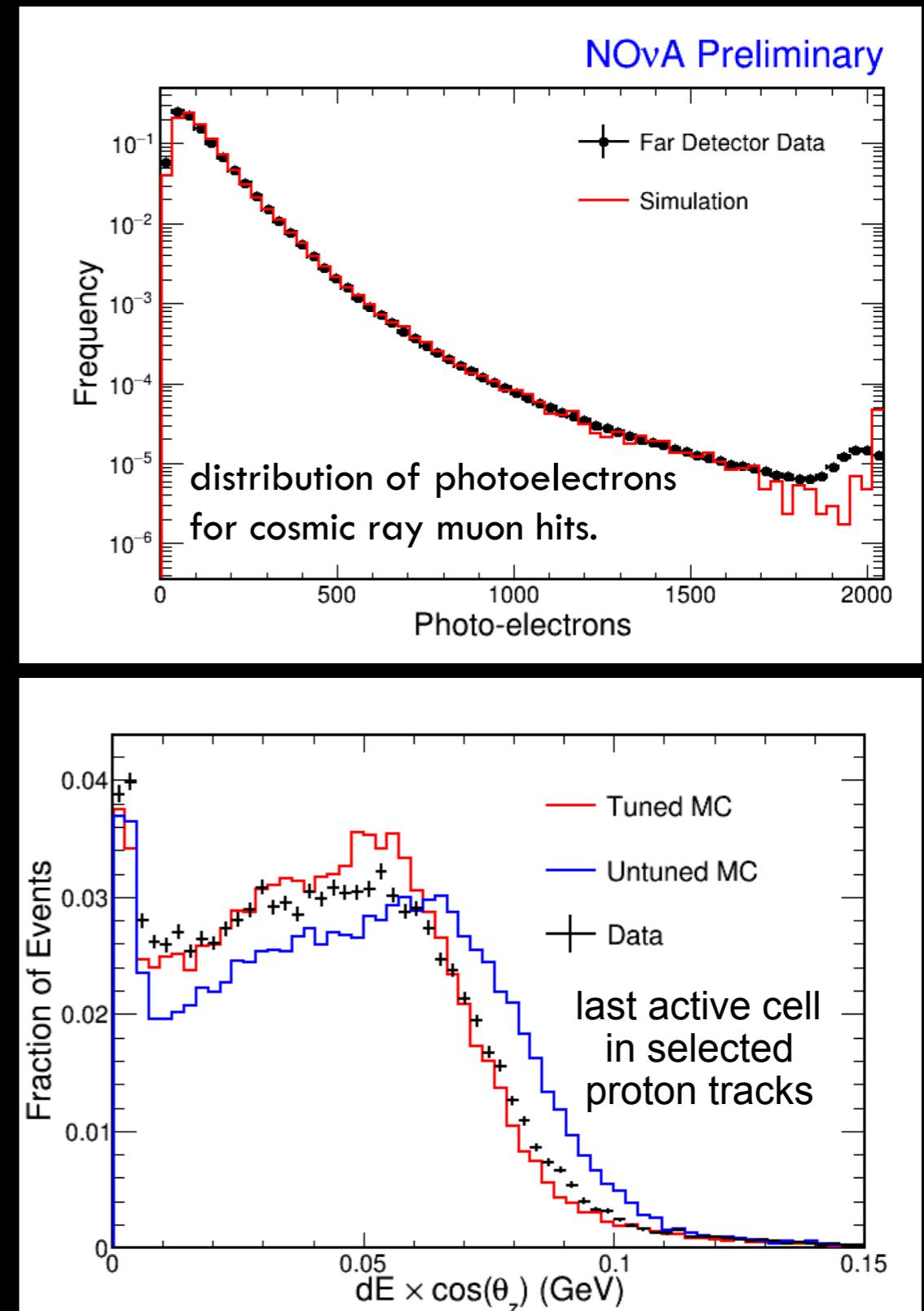


DETECTOR RESPONSE

- Detailed modeling includes:
 - fiber attenuation
 - light collection losses at cell ends
 - scintillator saturation
 - fiber length variation across modules
 - run-by-run matching of inactive channels
 - APD characteristics
 - amplifier noise
 - full digitized traces
 - readout electronics noise
 - signal shaping, digitization, zero suppression

Data requires more scintillator saturation in simulation for high dE/dx hits than usual.

Tune model to proton tracks.



NC COHERENT π^0

- A sizable π^0 sample can be isolated in the ND (used as calibration cross check).
- A selection for coherent π^0 has been developed using 2 prong events and requiring to have a very forward going shower in the final state.
- A preliminary version of this analysis has been used to constrain the coherent π^0 component of the electron appearance background.

